MULTILEVEL INVERTER

BASED

ELECTRIC TRACTION DRIVES

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Technology
in
Electrical Engineering
(Power Control & Drives)

By

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Dedicated to my beloved parents and brother

National Institute of Technology

Rourkela

CERTIFICATE

This is to certify that the thesis entitled "**MULTILEVEL INVERTER BASED ELECTRIC TRACTION DRIVES**" submitted by Miss. **SUBARNI PRADHAN** bearing **Roll No.211EE2137** in partial fulfillment of the requirements for the award of the degree of "**Master of Technology**" in Electrical Engineering specializing in "**Power Control and Drives"** at the National Institute of Technology, Rourkela is an authentic work carried out by her under my supervision. To the best of my knowledge and belief, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Date:
Place:

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ABBREVIATIONS

MLI	–Multilevel Inverter
IGBT	–Insulated Gate Bipolar Transistor
CMI	–Cascaded Multilevel Inverter
MPC	–Multiple Point Clamped
NPC	–Neutral Point Clamped
PWM	–Pulse Width Modulation
SPWM	–Sinusoidal Pulse Width Modulation
LS – PWM	–Level Shifted PWM
PS - PWM	–Phase Shifted PWM
IPD	–In Phase Disposition PWM
POD	–Phase Opposition Disposition PWM
APOD	–Alternate Phase Opposition Disposition
SHE	–Selective Harmonic Elimination
THD	–Total Harmonic Distortion
IM	–Induction Motor
VSI	–Voltage Source Inverter
GA	–Genetic Algorithm
NPC	–Neutral Point Clamped
CHB	–Cascaded H Bridge
CCC	–Capacitor Clamped Converter
SDCSs	–Separate DC Sources
FACTS	–Flexible Alternating Current Transmission system
HVDC	–High Voltage Direct Current
DTFC	–Direct Torque and Flux Control
IMD	–Induction Motor Drive
DC	–Direct Current
AC	–Alternative Current

ABSTRACT

Electric Railway Traction Drive has been introduced as a replacement to the existing steam and diesel run locomotives. Generally, an electric railway system requires a transformer to step down the high voltage (25 kV, 50 Hz) to the low voltage level (400 V, 50 Hz) which is fed to the traction motors. This transformer adds extra weight to the system along with the several losses and hence reduced efficiency. The railway electric traction requires high voltage operation. This can be achieved with the help of multilevel inverter (MLI) which eliminates the need of transformer in the railway traction system and also results in the reduction of the Total Harmonic Distortion (THD) of the voltage to be supplied to the traction motors.

In this paper, various modulation techniques of cascaded H-bridge inverter are analyzed, which can reduce THD for three-level inverter to multilevel topologies. Three methodologies adopting phase shifted carrier pulse width modulation, the level shifted carrier pulse width modulation and selective harmonic elimination (SHE) modulation concepts have been employed in this paper. The simulation of different modulation techniques has been done using MATLAB/SIMULINK. It was found that SHE modulation technique results in a lower value of THD. An eleven-level inverter with SHE modulation technique is used for electric traction drive; plugging and a combination of capacitive braking and DC injection braking method are employed for braking purpose. Different control methods like V/f Control and Direct Torque Control (DTC) are employed for speed control of traction motor. In DTC torque and flux was controlled directly by using required voltage vectors.

CHAPTER 1

1. INTRODUCTION

1.1 Overview:

Numerous industrial applications have begun to require higher power apparatus in recent years. Some medium voltage motor drives and utility applications require medium voltage and megawatt power level. For a medium voltage grid, it is troublesome to connect a single power semiconductor switch directly. For this reason, a family of multilevel power converter structure has been introduced as an alternative in high power and medium voltage situations. A multilevel converter not only achieves high power ratings, but also enables the use of renewable energy sources. Renewable energy sources such as photovoltaic, wind, and fuel cells can be easily interfaced to a multilevel converter system for a high power application [1-3].

The concept of multilevel converters has been introduced since 1975 [4]. The term multilevel began with the three-level converter [5]. Subsequently, several multilevel converter topologies have been developed [6-15]. However, the elementary concept of a multilevel converter to achieve higher power is to use a series of power semiconductor switches with several lower voltage dc sources to perform the power conversion by synthesizing a staircase voltage waveform. Capacitors, batteries, and renewable energy voltage sources can be used as the multiple dc voltage sources. The commutation of the power switches aggregate these multiple dc sources in order to achieve high voltage at the output; however, the rated voltage of the power semiconductor switches depends only upon the rating of the dc voltage sources to which they are connected.

The electric traction drives requires medium voltage and high power operation. Generally, the traction transformer steps down the high catenary voltage (25 KV, 50 Hz) to a low voltage level (400 V, 50 Hz) which is convenient for traction motors. This can be achieved with the help of multilevel inverters [16]. This bulky transformer reduces efficiency; increases weight, cost and floor space. In [17], it is shown that the multilevel inverters (MLI) can be directly connected to the high voltage supply and can step down the voltage. Thus, it eliminates the need of the transformer in traction system and also results in the reduction of the Total Harmonic Distortion (THD) of the voltage to be supplied to the traction motors.

1.2 Research Background

1.2.1 Multilevel Inverter:

Over the last decade, great advances have been made in multilevel inverter/converter topologies. In the literature, there are three traditional structures that were investigated in early and mid 1990s: the diode-clamped multilevel inverter, which came from the neutral-point clamped inverter invented in 1979 [5, 11, 12], the capacitor-clamped or flying capacitor MLI in 1992 [13], and the cascade H-bridge MLI in 1995 [8, 15]. Both traditional diode-clamped and capacitor-clamped multilevel inverters have a practical limit on the number of levels, because the number of respectively required clamping diodes and capacitors in both the topologies becomes excessive when the number of levels is high [8]. Large number of clamping diodes or capacitors are not required in Cascaded multilevel inverter, hence limitation of cascaded multilevel inverters is that they do not have a common dc link, thus cannot be directly applied to HVDC. Reconfiguring the cascaded structure as Modular multilevel converter overcomes this problem [22, 23]. Recently, many new multilevel inverter topologies are emerging. Some of them are mixed level hybrid multilevel cells, soft switched multilevel inverters , five level H-bridge Neutral point clamped (5L - HNPC), three level active Neutral point clamped (3L- ANPC), modular multilevel converter (MMC), cascaded matrix converter (CMC), transistor clamped converter (TCC), hybrid NPC -CHB , hybrid FC - CHB and many more [16].

Various modulation techniques can be used for the multilevel converters [6]. Some of them work with high switching frequency and some with fundamental switching frequency. Some high switching frequency modulation techniques are Sinusoidal Pulse Width Modulation (SPWM), Multicarrier Pulse Width Modulation (MPWM) and some fundamental switching frequency modulation techniques are Selective Harmonic Elimination (SHE) and Space Vector Modulation (SVM) and others.

Some features of multilevel converter are as follows [18, 19]:

• ***Staircase waveform quality:*** Multilevel converters not only can generate the output voltages with very low distortion, but also can reduce the *dv/dt* stresses; therefore electromagnetic compatibility (EMC) problems can be reduced.

• ***Common-mode (CM) voltage:*** Multilevel converters produce smaller CM voltage; therefore, the stress in the bearings of a motor connected to a multilevel motor drive can be reduced. Furthermore, CM voltage can be eliminated by using advanced modulation strategies.

• ***Input current:*** Multilevel converters can draw input current with low distortion.

•***Switching frequency:*** Multilevel converters can operate at both fundamental switching frequency and high switching frequency PWM. It should be noted that lower switching frequency usually means lower switching loss and higher efficiency.

Limitations of multilevel converter are as follows [19, 20]:

i. With the increase in the level, there is an increase in control complexity and the voltage imbalance problem arises.

ii. The design of simple and fast modulation techniques are also one of the technological problems.

iii. Even though the low voltage semiconductor devices are used, each device should have its own gate circuit, making it expensive and complex.

1.2.2 Electric Traction Drive:

Concept of Electric Drive technology was born in 19th century, and widely used in industry, agriculture, transport and daily life application in 20th century. According to [32], the class 1822 dual-voltage locomotive of Austrian Railways (OBB) is the first railway traction drive using a three-level PWM converter and inverter.

1.2.3 Braking of Traction Motor:

Over the years, development of effective braking systems for three-phase induction motors used in industrial drives has been a subject of study. Different braking strategies like plugging, DC injection braking, capacitor self-excitation braking are being used [33-35]. Depending upon various factors such as application, energy requirement, and cost, complexity of control circuit, effectiveness, and reliability, suitable braking system is adapted.

1.2.4 Direct Torque Control of Induction Motor:

Direct torque control (DTC) is one of the high-powered adjustable speed methods of induction motors. DTC is the advanced vector control method. The main principle of DTC is that according to the states of magnetic linkage and torque an optimal voltage vectors is chosen from the control table, then the switches of inverter are controlled. Hence the magnetic linkage and torque can be limited in the range of an admissible error, thereby magnetic linkage and torque can be controlled directly. The characteristic of DTC is that the control of system is simple and directly and the dynamic response of system is fast. The disadvantage of DTC control scheme is that, this scheme operates with a variable inverter switching frequency. Again, an accurate stator flux estimation method is necessary, which requires an accurate motor model and fast sampling [40].

1.3 Motivation

1.3.1 Multilevel Inverter:

Generally, advanced power electronic inverters are required to meet the high power (>250 kW) demand of the large electric drives which are used for heavy duty electric and hybrid electric vehicles (EV's). These large electric drives will result in lower emission, increased fuel efficiency and better vehicle performance like acceleration and braking. It is very hard to connect a single power semiconductor device directly to the high voltage grid. Transformer-less multilevel inverters are best suited for this application because of the high volt-ampere ratings possible with these inverters [20]. Also with the help of the multilevel inverter, the transformation of the voltage level can be done without the help of the bulky transformer. This resulted in transformer-less traction drives [16]. Thus, the multilevel inverter prevents the motor damage and thereby increases the efficiency of the drive.

1.3.2 Electric Traction Drive in Railway System:

Earlier the steam and diesel tractions were used in the railway vehicles, which were very expensive and polluted form of traction. For this reason, a new form of traction system has been introduced in the railway system, which is known as electric traction system. It is not only environmental friendly but also cost effective in terms of the fuel cost. If railway vehicle has possibility to make railway operation more efficient, one can use electrical brake that can minimize vehicle maintenance staffs and simplifies train operation. Introducing this technology, all brake force from the top speed to zero is generated electrically and there is no mechanical wear of brake materials.

1.3.3 DC Dynamic Braking:

Dynamic braking is a process in which kinetic energy of rotor is dissipated in external resistor as heat energy [45]. It is an electrical braking process used in many industrial applications. Dynamic braking allows sudden stop of electrical motor without mechanical wear and tear.

1.3.4 Direct Torque Control of Induction Motor:

In order to improve the dynamic performance of induction motor drives for electric vehicle propulsion, vector control technique is preferred. Disadvantages of vector controlled drives are complexity of coordinate transformation, inclusion of shaft encoder, and parameter dependency [41]. These problems can be overcome by using Direct Torque Control (DTC) of induction motor which is the advanced vector control method [42]. By using this control methoddecoupled control of flux and torque is possible without using co-ordinate transformation. The advent of direct torque control (DTC) for induction machines in the 1980's as proposed by M. Depenbrock [43] and Takahashi [42].

1.4 Objectives

i. To give Brief Description on Multilevel Converters, Circuit Topologies, Working Principles.

ii. To implement various type of modulation technique in IGBT based cascaded multilevel inverter and use the best modulation technique in the cascaded multilevel rectifier inverter configuration.
iii. To Simulate Generalized Cascaded H-bridge Multilevel Inverter for Different Levels using different modulation techniques.
iv. To observe THD of each level and each modulation technique.
v. To Design and develop an IGBT based cascaded multilevel inverter drive for electric railway traction.
vi. To implement plugging and a combination of capacitive and DC injection braking to this type of drive.
vii. To implement a control strategy for the traction motor.

1.5 Thesis Outline

In this thesis, the modelling of cascaded H-bridge multilevel inverter, various modulation techniques of multilevel inverter, performance of traction drive under braking conditions and various speed control strategies are analyzed. This thesis contains six chapters.

Chapter 1 Presents a brief idea about Electric Traction system. It also contains the introduction, research background, motivation and objective.

Chapter 2 Discusses the different topologies of multilevel inverter along with their advantages, disadvantages and applications.

Chapter 3 Describes the different modulation technique used for multilevel inverter

Chapter 4 Discusses about the electric traction system. A block diagram of electric traction system with two braking phenomenon was presented in this chapter.

Chapter 5 Describes speed control method of traction motor. In this chapter a scalar control and an advanced vector control method or direct torque and flux control of induction motor is described.

Chapter 6 Gives the overall conclusion and scope for future work of the project.

CHAPTER 2

2. MULTILEVEL INVERTERS

2.1 Introduction

Multilevel inverters include an array of power semi-conductors and DC voltage sources, the output of which generate voltage with stepped waveforms. By increasing the number of levels in the multilevel inverters, the output voltages will have more steps in generating a staircase waveform, which approaches a sinusoidal waveform with reduced harmonic distortion.

Multilevel inverters are basically classified into three types [18, 19]:

i. Diode Clamped multilevel inverter
ii. Capacitor Clamped Multilevel Inverter
iii. Cascaded H-bridge Multilevel Inverter

2.2 Diode-Clamped Multilevel Inverter

The diode-clamped inverter provides multiple voltage levels through connection of the phases to a series bank of capacitors. According to the original invention, the concept can be extended to any number of levels by increasing the number of capacitors. Early descriptions of this topology were limited to three-levels where two capacitors are connected across the dc bus resulting in one additional level. The additional level was the neutral point of the dc bus, so the terminology neutral point clamped (NPC) inverter was introduced. However, with an even number of voltage levels, the neutral point is not accessible, and the term multiple point clamped (MPC) is sometimes applied. Due to capacitor voltage balancing issues, the diode-clamped inverter implementation has been mostly limited to the three-level. Because of industrial developments over the past several years, the three-level inverter is now used extensively in industry applications. Although most applications are medium-voltage, a three-level inverter for 480 V is on the market.

In general, for am level diode clamped inverter, for each leg 2*(m-1) switching devices, (m-1)*(m-2) clamping diodes and (m-1) dc link capacitors are required. When m is sufficiently high, the number of diodes and the number of switching devices will increase and make the system impracticable to implement. If the inverter runs under pulse width modulation (PWM), the diode reverse recovery of these clamping diodes becomes the major design challenge. Fig.2.1 shows the one phase leg of five-level diode-clamped inverter consists of four DC link capacitors C_1, C_2, C_3 and C_4, twelve clamping diodes. For DC bus voltage V_{dc}, the voltage across each capacitor is $V_{dc}/4$, and blocking voltage of each device will be limited to $V_{dc}/4$ through clamping diodes. Table.2.1 shows the switching states of five-level Diode-clamped inverter. When switches S_1-S_4 are on output voltage level (V_o) will be $V_{dc}/2$.To get output voltage level equal to $V_{dc}/4$ upper switches S_3 and S_4 and lower switches S_1' and S_2' are made on. To get output voltage level equal to $-V_{dc}/4$ one upper switch S_4 and three lower switches S_1'-S_3' are made on. When all the lower switches are made on the output voltage will be equal to $-V_{dc}/2$.

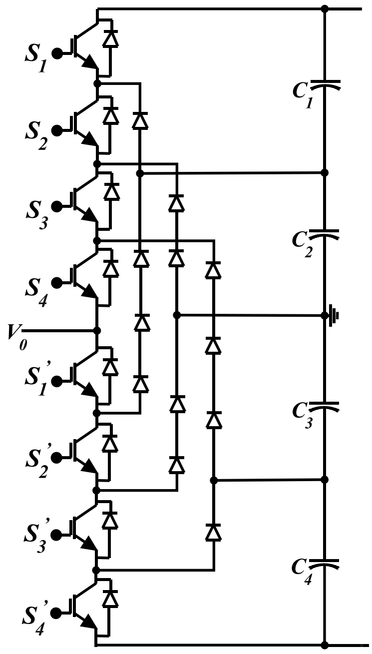


Fig.2.1 Five-level Diode-Clamped Inverter (one phase leg)

Table 2.1 Switching States of Five-level Diode-Clamped Inverter

Output(V_o)	S_1	S_2	S_3	S_4	S_1'	S_2'	S_3'	S_4'
V_5=$V_{dc}/2$	1	1	1	1	0	0	0	0
V_4=$V_{dc}/4$	0	1	1	1	1	0	0	0
V_3=0	0	0	1	1	1	1	0	0
V_2=$-V_{dc}/4$	0	0	0	1	1	1	1	0
V_1=$-V_{dc}/2$	0	0	0	0	1	1	1	1

Advantages of Diode Clamped Inverter [16, 19, 20]:

- The THD decreases with the increase in the number of levels. Thus avoid the need of filters.
- Since all the devices are switched at the fundamental frequency, the efficiency of inverter is high.
- Reactive power flow can be controlled.
- Capacitors can be pre-charged as a group.
- Since all the phases share a common dc bus, the capacitance requirements are minimized.

Some Disadvantages of Diode Clamped Inverter [16, 19, 20]:

- There is a quadratic increase of clamping diodes with the increase in the level.
- It is difficult to control the real power flow of the individual converter in multi-converter systems as the intermediate dc levels will tend to overcharge or discharge without precise monitoring and control.
- Even though each active switching device voltage stress is limited to $V_{dc}/(m-1)$, the clamping diodes must have different voltage ratings for reverse voltage blocking.

2.3 Capacitor-Clamped Multilevel Inverter

Meynard and Foch introduced a flying-capacitor-based inverter in 1992 [13]. This is also known as flying-capacitor MLI. The structure of this inverter is similar to that of the diode-clamped inverter except that instead of using clamping diodes, the inverter uses capacitors in their place. This configuration is also known as Capacitor-Clamped multilevel inverter. The circuit topology of the Capacitor-Clamped multilevel inverter is shown in Fig.2.2. This topology has a ladder structure of dc side capacitors, where the voltage on each capacitor differs from that of the next capacitor. The voltage increment between two adjacent capacitor legs gives the size of the voltage steps in the output waveform. Table.2.2 shows the switching states of five-level capacitor-clamped inverter. When switches S_1-S_4 are on output voltage level (V_o) will be $V_{dc}/2$.To get output voltage level equal to $V_{dc}/4$ upper switches S_3 and S_4 and lower switches S_1' and S_2' are made on. To get output voltage level equal to $-V_{dc}/4$ one upper switch S_4 and three lower switches S_1'-S_3' are made on. When all the lower switches are made on the output voltage will be equal to $-V_{dc}/2$.

One advantage of the capacitor-clamped inverter is that it has redundancies for inner voltage levels; in other words, two or more valid switch combinations can synthesize an output voltage. Unlike the diode-clamped inverter, the capacitor-clamped inverter does not require all of the switches that are on (conducting) be in a consecutive series. Moreover, the capacitor-clamped inverter has phase redundancies, whereas the diode-clamped inverter has only line-line redundancies [2, 3, 21]. These redundancies allow a choice of charging/discharging specific capacitors and can be incorporated in the control system for balancing the voltages across the various levels.

In addition to the (m-1) dc link capacitors, the m-level flying-capacitor multilevel inverter will require (m-1)*(m-2)/2 auxiliary capacitors per phase if the voltage rating of the capacitors is identical to that of the main switches. One application proposed in the literature for the multilevel capacitor-clamped inverter is static var generation [2, 3].

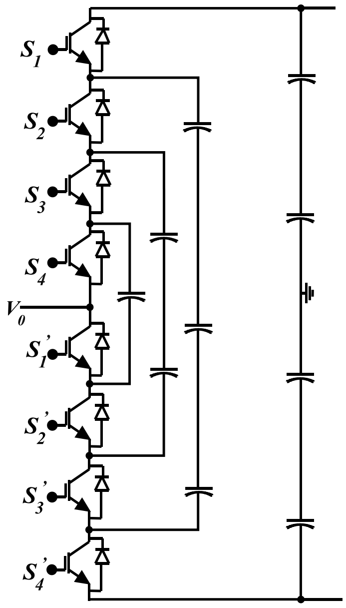


Fig.2.2Five-Level Capacitor-clamped Inverter (one phase leg)

Table 2.2 Switching States of Five-level Capacitor-clamped Inverter

Output(V_o)	S_1	S_2	S_3	S_4	S_1'	S_2'	S_3'	S_4'
$V_5=V_{dc}/2$	1	1	1	1	0	0	0	0
$V_4=V_{dc}/4$	0	1	1	1	1	0	0	0
$V_3=0$	0	0	1	1	1	1	0	0
$V_2=-V_{dc}/4$	0	0	0	1	1	1	1	0
$V_1=-V_{dc}/2$	0	0	0	0	1	1	1	1

Advantages of multilevel Capacitor-Clamped Inverter [19, 20] :

- THD is lowered with the increase in the level as in NPC.
- Both the real and reactive power flow can be controlled.
- Large amounts of storage capacitors provide ride through capability during power outages.
- Phase redundancies are available for balancing the voltage levels of the capacitors.
- By proper selection of capacitor combination, the capacitor charge can be balanced.

Disadvantages of multilevel Flying Capacitor Inverter [19, 20]:

- Control is complicated to track the voltage levels for all of the capacitors.
- Pre-charging of all the capacitors to the same voltage level and startup are complex.
- Switching utilization and efficiency are poor for real power transmission.
- The large numbers of capacitors are more expensive and bulkier than clamping diodes in multilevel diode-clamped converters.

- Packaging is more difficult in inverters with a high number of levels.

2.4 Cascaded H-bridge Multilevel Inverter

A three-phase structure of an m-level cascaded inverter is illustrated in Fig.2.3. Each separate dc source (SDCS) is connected to a single-phase full-bridge, or H-bridge, inverter. Each inverter level can generate three different voltage outputs, $+V_{dc}$, 0, and $-V_{dc}$ by connecting the dc source to the ac output by different combinations of the four switches, S_1, S_2, S_3, and S_4. To obtain $+V_{dc}$, switches S_1 and S_4 are turned on, whereas $-V_{dc}$ can be obtained by turning on switches S_2 and S_3. By turning on S_1 and S_2 or S_3 and S_4, the output voltage is 0. The ac outputs of each of the different full-bridge inverter levels are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs. The number of output phase voltage levels m in a cascade inverter is defined by m = 2s+1, where s is the number of separate dc sources. An example of an 11-level cascaded H-bridge inverter and phase voltage waveform for an 11-level cascaded H-bridge inverter with 5 SDCSs and 5 full bridges is shown in Fig.2.4 and Fig.2.5 respectively. The phase voltage $v_{an} = v_{a1} + v_{a2} + v_{a3} + v_{a4} + v_{a5}$. For a stepped waveform such as the one depicted in Figure 5, with s steps, the Fourier Transform for this waveform follows [15,19]

$$V(\omega t)=\frac{4V_{dc}}{\pi}\sum_{n}\left[\cos(n\theta_1)+\cos(n\theta_2)+\ldots+\cos(n\theta_s)\right]\frac{\sin(n\omega t)}{n} \quad \text{Where n=1, 3, 5, 7 …..} \qquad (2.1)$$

Advantages of cascaded H-bridge Multilevel Inverter [2, 24]

- Separate DC sources eliminate the need of the voltage balancing circuits.
- Suitable for medium voltage, high power applications.
- No clamping diodes present as in NPC.
- Low voltage switching devices required.
- No voltage balancing capacitors present in FC.
- It can work at reduced power level when one of its cells is damaged.
- Soft switching techniques can be applied to cascaded H-bridge (CHB) Inverter.
- No transformer required as in multi-pulse inverters.
- Modular in structure so packing and circuit layout is easier.

Disadvantages of cascaded H-bridge Inverter [2, 24]

- It needs separate dc sources for real power conversions, and thus its applications are somewhat limited.

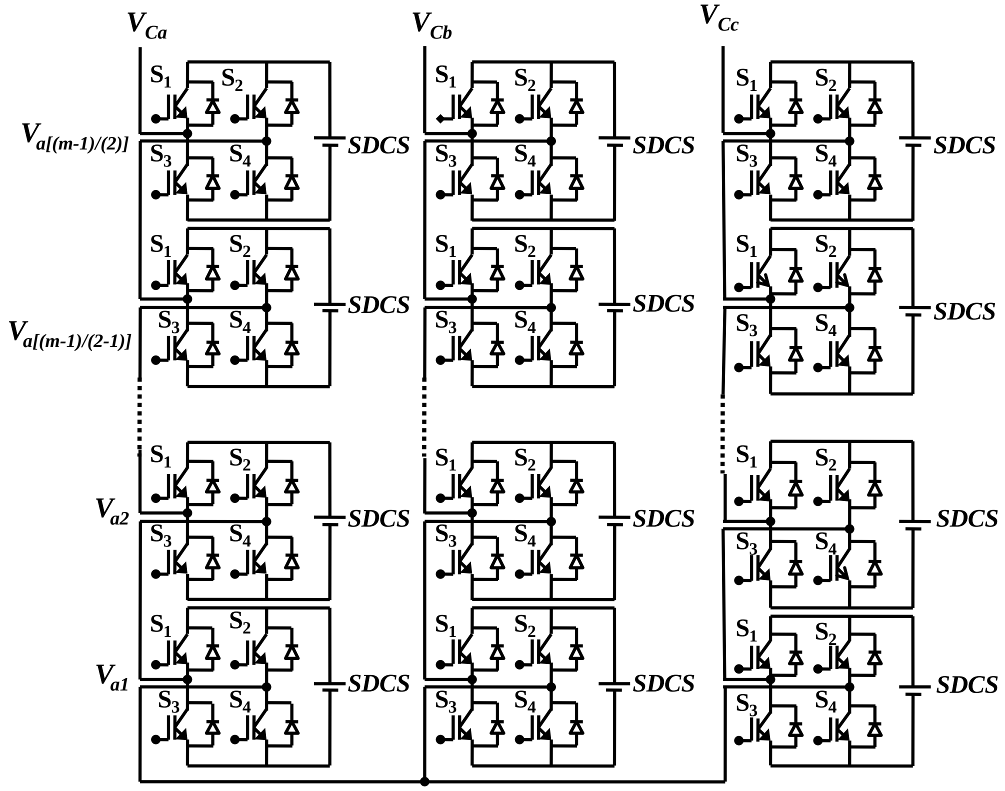


Fig.2.3 Three-Phase structure of cascaded H-bridge Multilevel Inverter (m-level)

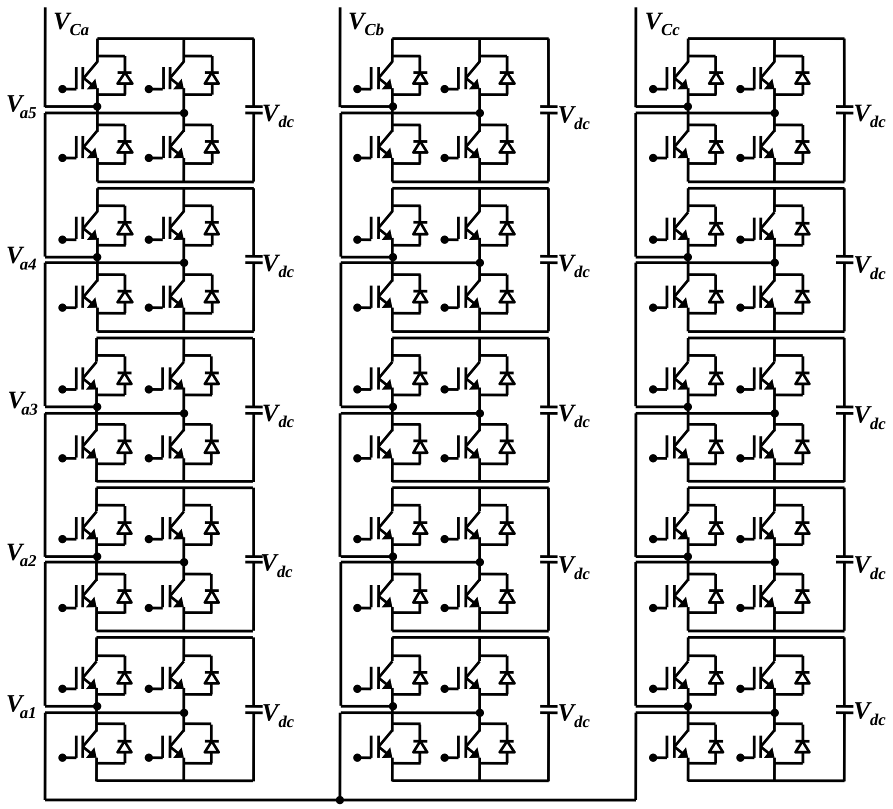


Fig.2.4 Three-Phase Eleven-Level Cascaded H-bridge Inverter

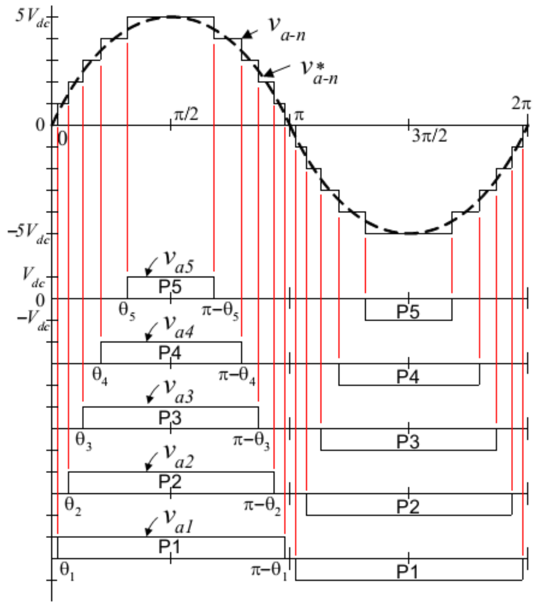


Fig.2.5 Output Phase Voltage Waveform of an eleven-level cascaded H-bridge Inverter

Table.2.3 shows the equipments required in different types of multilevel inverter. According to this table, same amount of main switching devices and main diodes are required in all the types of multilevel inverter. Clamping diodes are required only in Diode-Clamped multilevel inverter. Balancing capacitors are required only in Capacitor-Clamped multilevel inverter. Requirement of DC bus capacitor is half in CHB inverter than Diode-clamped and Capacitor-Clamped inverter. It proves that less amount of equipments are required in CHB inverter.

Table.2.3 Equipments Required in Different types of multilevel inverter

Converter Type	Diode Clamped	Capacitor Clamped	Cascaded H-bridge inverter
Main switching devices	(m-1)*2	(m-1)*2	(m-1)*2
Main diodes	(m-1)*2	(m-1)*2	(m-1)*2
Clamping Diodes	(m-1)*(m-2)	0	0
DC Bus Capacitors	(m-1)	(m-1)	(m-1)/2
Balancing Capacitors	0	(m-1)*(m-2)/2	0

2.5 Applications of Multilevel Inverter

All three multilevel inverters can be used in reactive power compensation without having the voltage unbalance problem. Multilevel cascaded inverters have been proposed for such applications as static var generation, an interface with renewable energy sources, and for battery-based applications. Three-phase cascaded inverters can be connected in wye, or in delta. Peng has demonstrated a prototype multilevel cascaded static var generator connected in parallel with the electrical system that could supply or draw reactive current from an electrical system [25-27]. The inverter could be controlled to either regulate the power factor of the current drawn from the source or the bus voltage of the electrical system where the inverter was connected. Peng [28] and Joos [29] have also shown that a cascade inverter can be directly connected in series with the electrical system for static var compensation. Cascaded inverters are ideal for connecting renewable energy sources with an ac grid, because of the need for separate dc sources, which is the case in applications such as photovoltaic or fuel cells and FACTS applications including var/harmonic compensation, series compensation, phase shifting and voltage balancing because each DC capacitor voltage can be self-maintained and independently controlled without additional DC sources.

Cascaded inverters have also been proposed for use as the main traction drive in electric vehicles, where several batteries or ultra-capacitors are well suited to serve as SDCSs [19, 26]. The cascaded inverter could also serve as a rectifier/charger for the batteries of an electric vehicle while the vehicle was connected to an ac supply. The cascade inverter can act as a rectifier in a vehicle that uses regenerative braking.

2.6 Summary

CHB Inverters enable direct parallel or series transformer-less connection to medium- and high-voltage power systems. In short, the cascade inverter is much more efficient and suitable for utility applications than traditional multi-pulse and pulse width modulation (PWM) inverters. CHB inverters can be efficiently used for utility applications including utility interface of renewable energy, voltage regulation, var compensation, and harmonic filtering in power systems. Cascaded multilevel inverter can eliminate the bulky transformers of multi-pulse inverter; can generate almost sinusoidal waveform voltage and current. Because of its modular and simple structure, the cascade inverter can be stacked up to a practically unlimited number of levels. These features make it useful for medium to high voltage power system application.

CHAPTER 3

3. MODULATION TOPOLOGIES OF MULTILEVEL INVERTER

3.1 Introduction

Various modulation techniques are used for the multilevel converters [19]. Fig.3.1 shows the classification of different modulation techniques used for the multilevel inverter. Depending upon the switching frequency, modulation techniques are broadly divided into 2 parts as fundamental switching frequency and high switching frequency pulse width modulation (PWM). Space vector control and selective harmonic elimination (SHE) modulation techniques come under fundamental switching frequency. Space vector pulse width modulation (SVPWM), Phase shifted PWM (PSPWM), level shifted PWM (LSPWM) are high switching frequency PWM techniques. LSPWM is again divided into three parts:-

i. In phase disposition (IPD) PWM
ii. Phase opposition disposition (POD) PWM
iii. Alternative phase opposition disposition (APOD) PWM

PSPWM and LSPWM techniques are also called as multicarrier PWM techniques [46].

Sinusoidal Pulse Width Modulation (SPWM) can be implemented in both two level and multilevel inverters. In SPWM, a sinusoidal reference signal and a high frequency carrier signal (triangular signal) are compared to give two states (high or low). The amplitude of the fundamental component of the output voltage of the inverter can be controlled by varying Modulation Index (M_I). Modulation Index is defined as the ratio of the magnitude of the reference signal (V_r) to that of the magnitude of the carrier signal (V_c). Thus, by keeping V_c constant and varying V_r, the modulation index can be varied.

The two main advantages of PWM inverters in comparison to square-wave inverters are (i) control over output voltage magnitude (ii) reduction in magnitudes of unwanted harmonic voltages. Good quality of output voltage in SPWM requires the modulation index (m) to be less than or equal to 1.0. For m>1 (over-modulation), the fundamental voltage magnitude increases but quality of output waveform decreases. The maximum fundamental voltage that the SPWM inverter can give the output (without resorting to over-modulation) is only 78.5% of the fundamental voltage output by square-wave inverter.

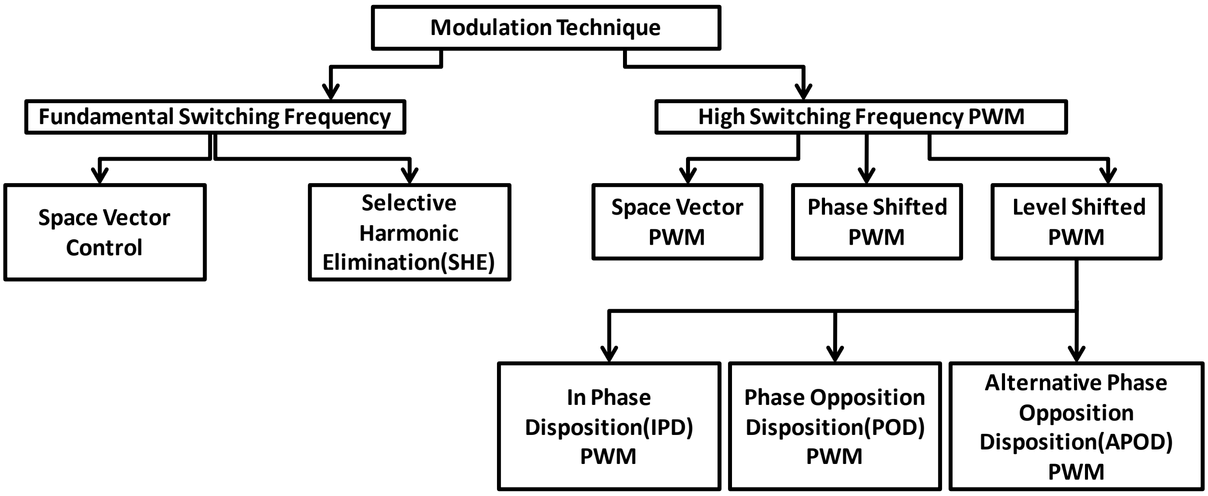


Fig.3.1 Classification of Different Types of Modulation Technique

3.2 Multicarrier Pulse Width Modulation Techniques

The carrier based PWM techniques for cascaded multilevel inverter can be broadly classified into: phase shifted modulation and level shifted modulation [31]. In both the techniques, for an m level inverter, (m-1) triangular carrier waves are required. And all the carrier waves should have the same frequency and the same peak to peak magnitude so that they fully occupy contiguous bands over the range $+V_{dc}$ to $-V_{dc}$. A single sinusoidal reference is then compared with each carrier to determine the switched output voltages for the converter.

3.2.1 Level Shifted Multicarrier pulse width modulation technique:

There are 3 schemes for the Level-Shifted multicarrier modulation:-

i. In Phase disposition (IPD):- In this modulation technique, all the carriers are in phase and reference wave is 3-phase sinusoidal wave. Carrier and reference waves of 7-level inverter in IPD modulation technique are shown in Fig.3.2.

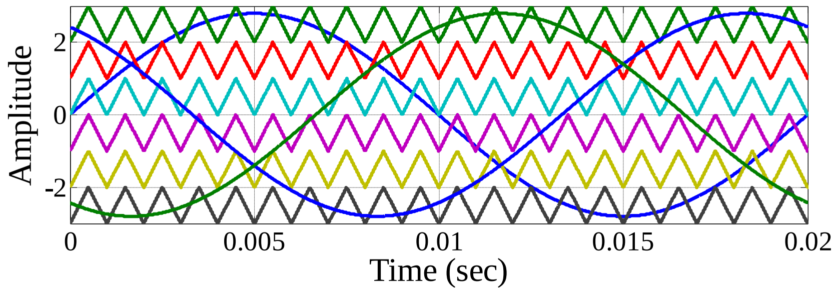


Fig.3.2 In Phase Disposition PWM for 7-level CHB inverter

ii. Phase opposition disposition (POD):- In this type of modulation technique, the carriers above the sinusoidal reference zero point are in phase, but shifted by 180^{o} out of phase with those below the zero reference point. Fig.3.3 shows carrier and reference waves for 7-level inverter with POD modulation technique.

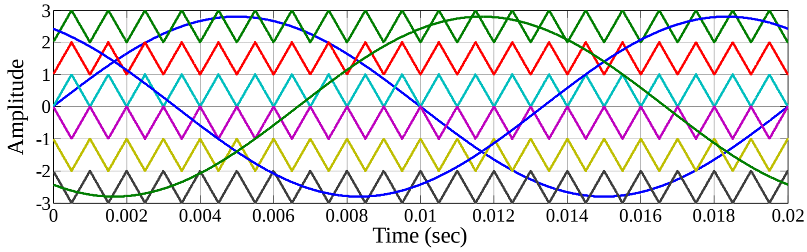


Fig.3.3 Phase Opposition Disposition PWM for 7-level CHB inverter

iii. Alternative phase opposition disposition (APOD):- In this type of modulation technique, each carrier is phase shifted by 180^{o} from its adjacent carrier. The arrangement of carrier and reference waves for a 7-level inverter with APOD modulation technique is shown in Fig.3.4.

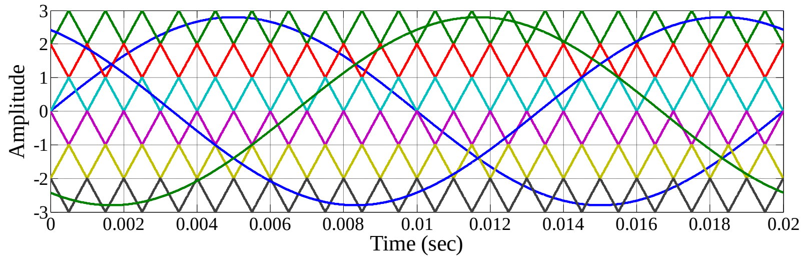


Fig.3.4 Alternate Phase Opposition Disposition PWM for 7-level CHB inverter

3.2.2 Phase Shifted Multicarrier pulse width modulation technique:

In Phase Shifted multicarrier Modulation Technique, all the triangular carriers have the same frequency and the same peak-to-peak amplitude but there is a phase shift between any two adjacent carrier waves, given by $\Phi_{cr} = 360^{o}/(m-1)$

The modulating signal is usually a three phase sinusoidal wave with adjustable amplitude and frequency. The gate signals are generated by comparing the modulating wave with the carrier-waves as shown in Fig.3.5.

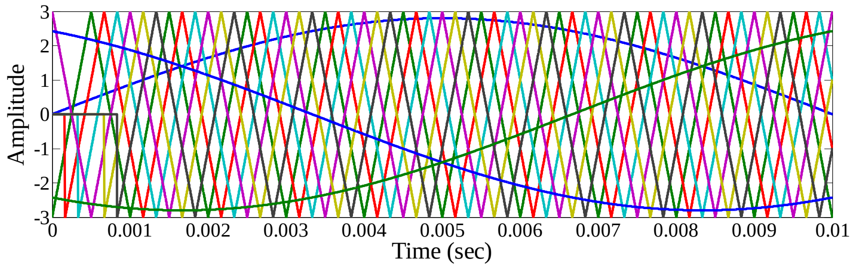


Fig.3.5 Phase Shifted PWM for 7-level CHB inverter

3.3 Simulation Results

3.3.1 Output Voltage Waveform and THD of Cascaded Multilevel Inverters using Different Types of Level Shifted Modulation Technique:

A) In Phase Disposition Modulation Technique:

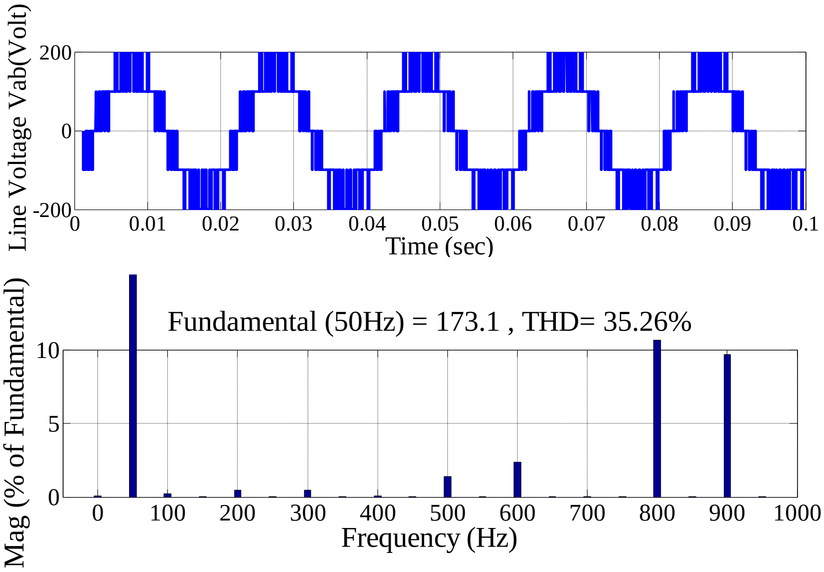


Fig.3.6 (a) Line Voltage and THD of 3-Level Inverter

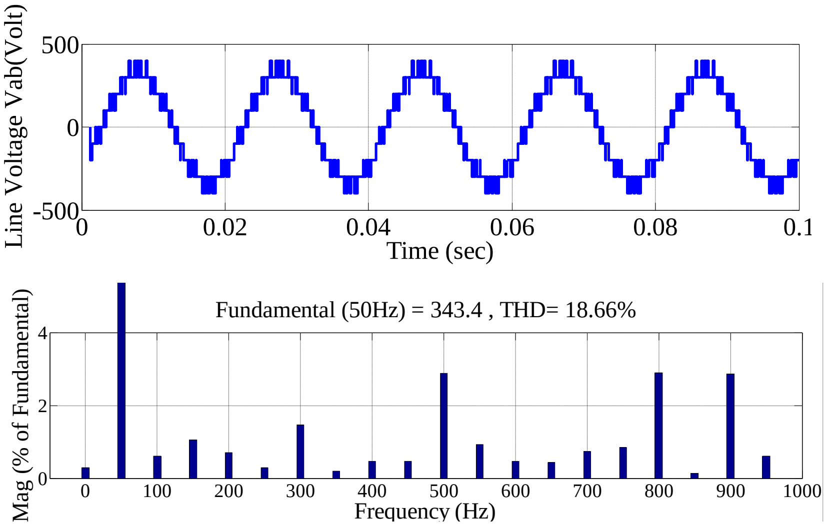


Fig.3.6 (b) Line Voltage and THD of 5-Level Inverter

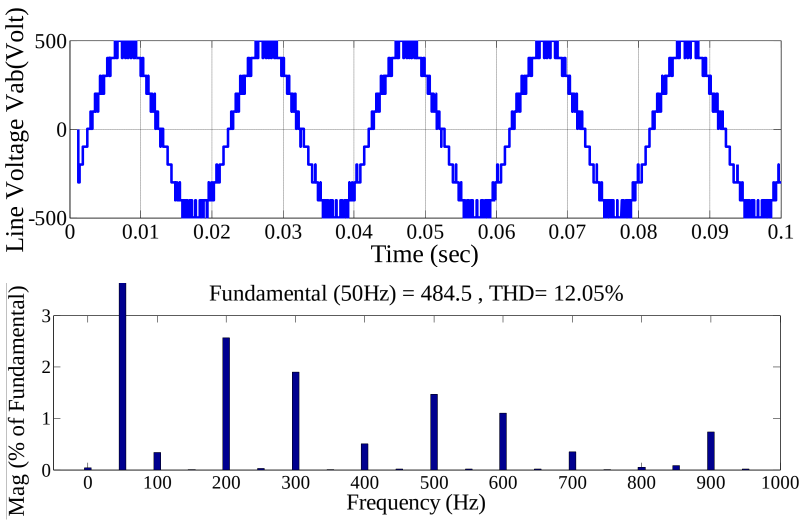


Fig.3.6 (c) Line Voltage and THD of 7-Level Inverter

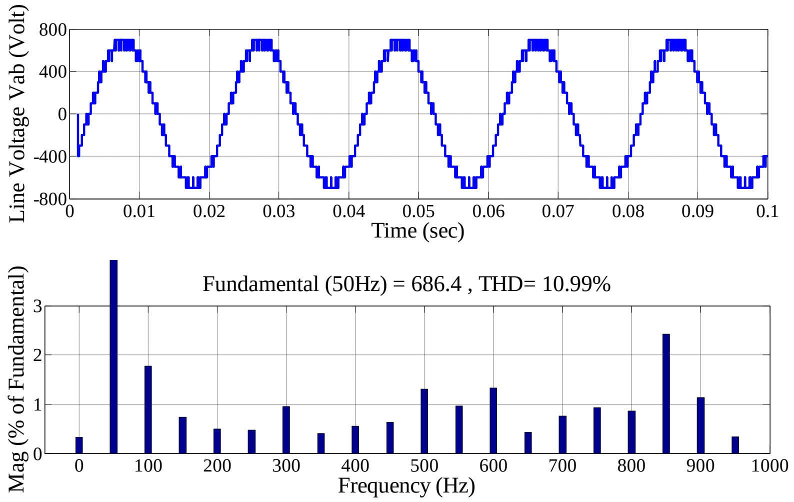


Fig.3.6 (d) Line Voltage and THD of 9-Level Inverter

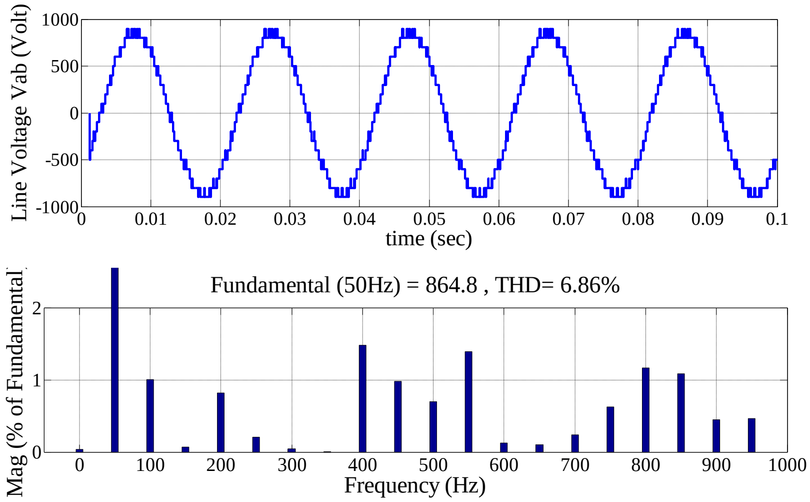


Fig.3.6 (e) Line Voltage and THD of 11-Level Inverter

B) Phase Opposition Disposition Modulation Technique:

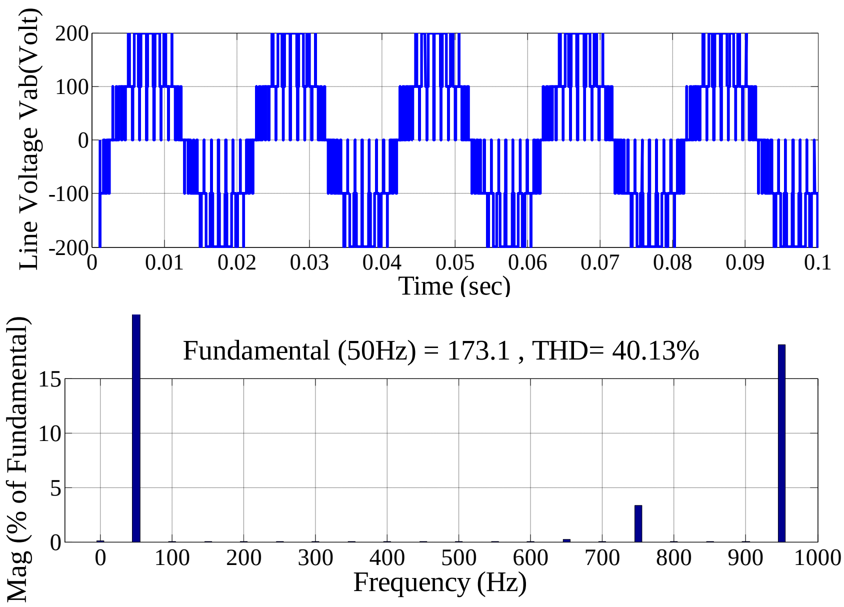


Fig.3.7 (a) Line Voltage and THD of 3-Level Inverter

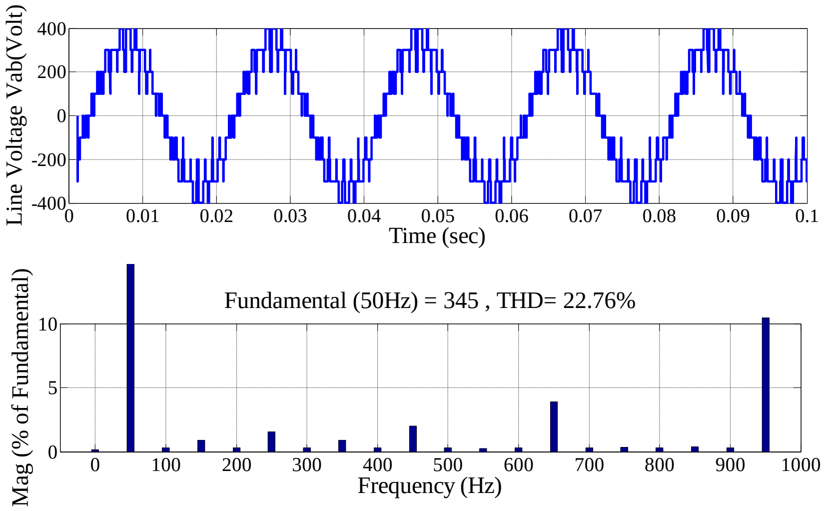


Fig.3.7 (b) Line Voltage and THD of 5-Level Inverter

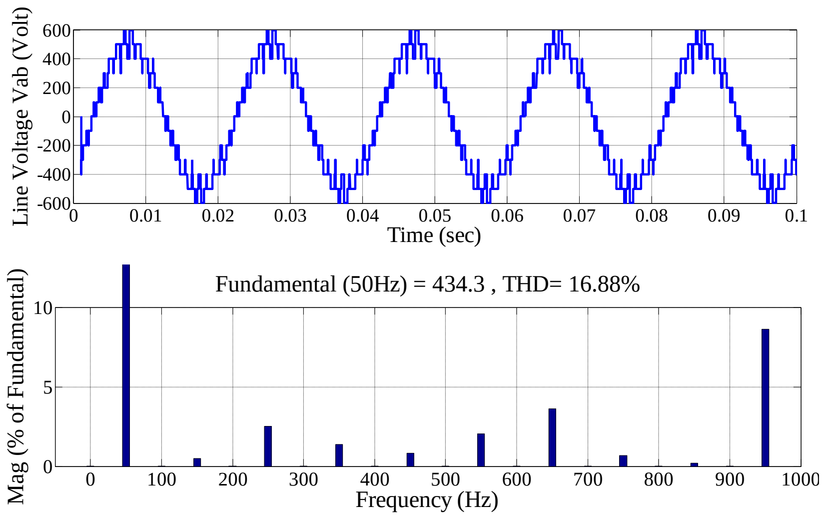


Fig.3.7 (c) Line Voltage and THD of 7-Level Inverter

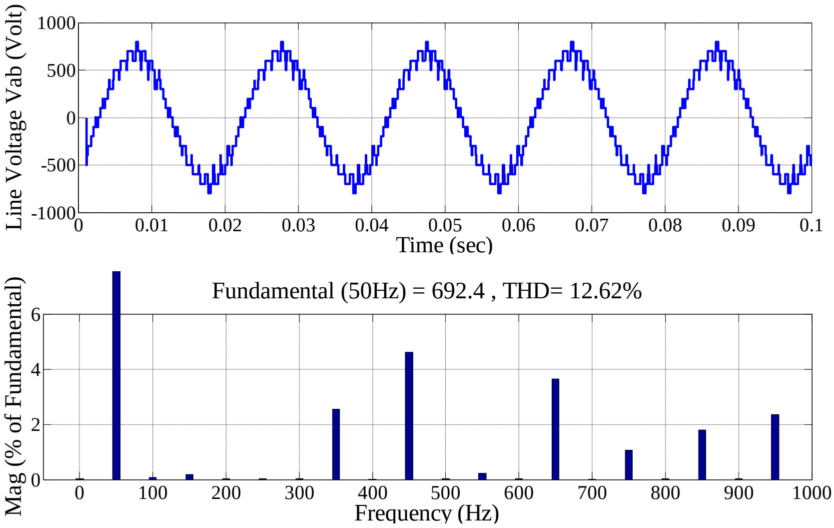


Fig.3.7 (d) Line Voltage and THD of 9-Level Inverter

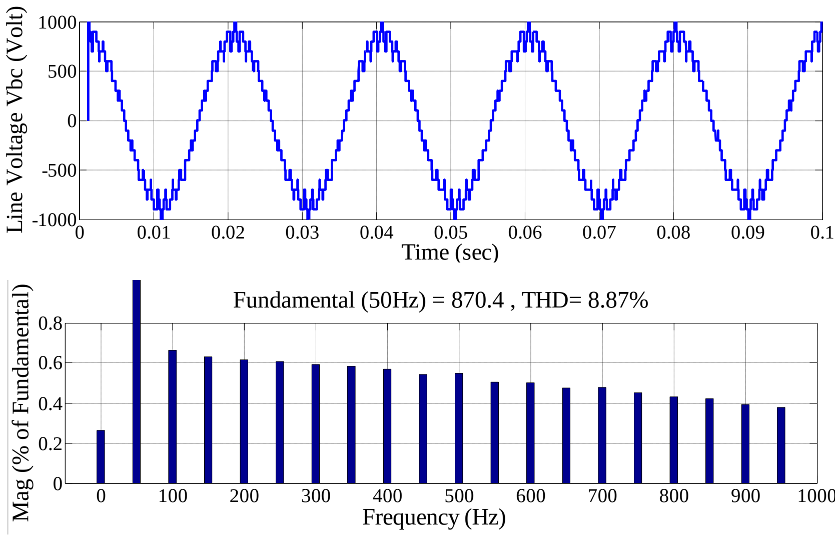


Fig.3.7 (e) Line Voltage and THD of 11-Level Inverter

C) Alternate Phase Opposition Disposition Modulation Technique:

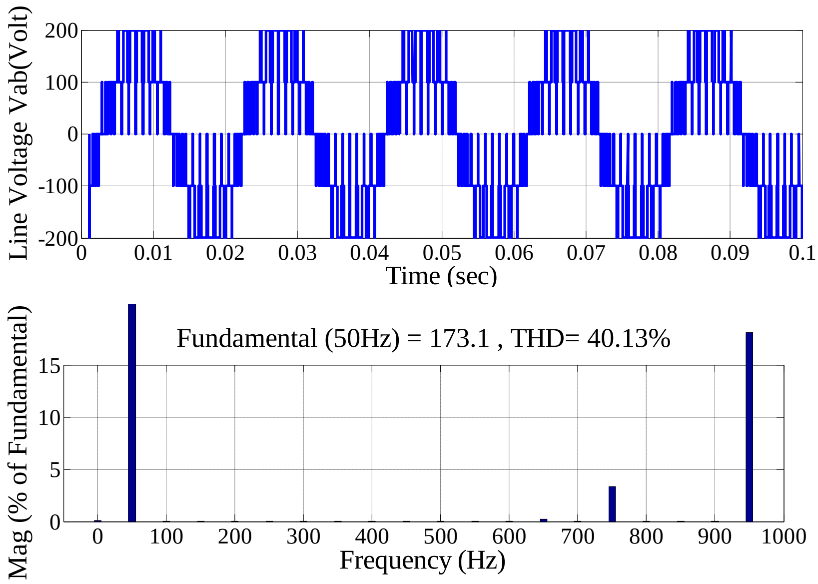


Fig.3.8 (a) Line Voltage and THD of 3-Level Inverter

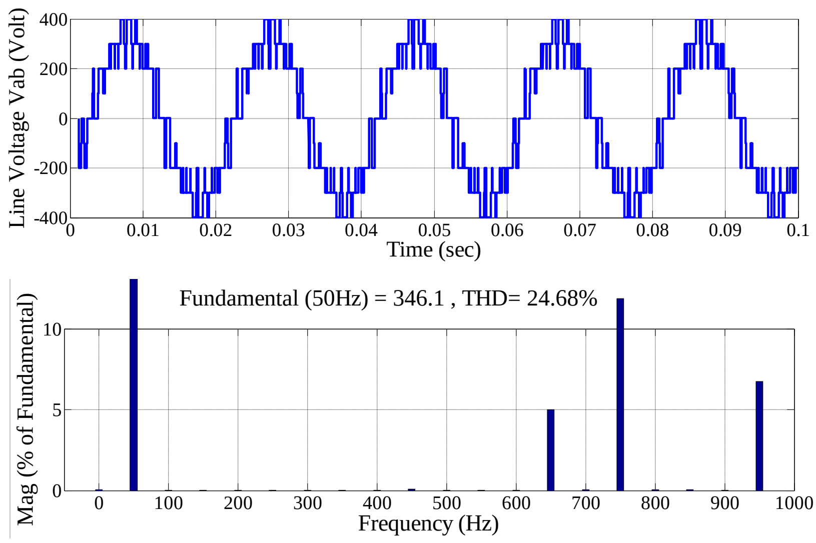


Fig.3.8 (b) Line Voltage and THD of 5-Level Inverter

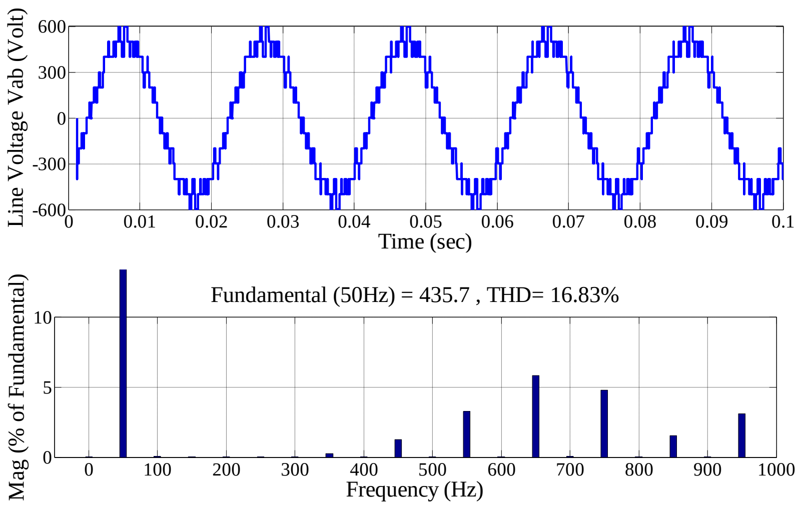


Fig.3.8 (c) Line Voltage and THD of 7-Level Inverter

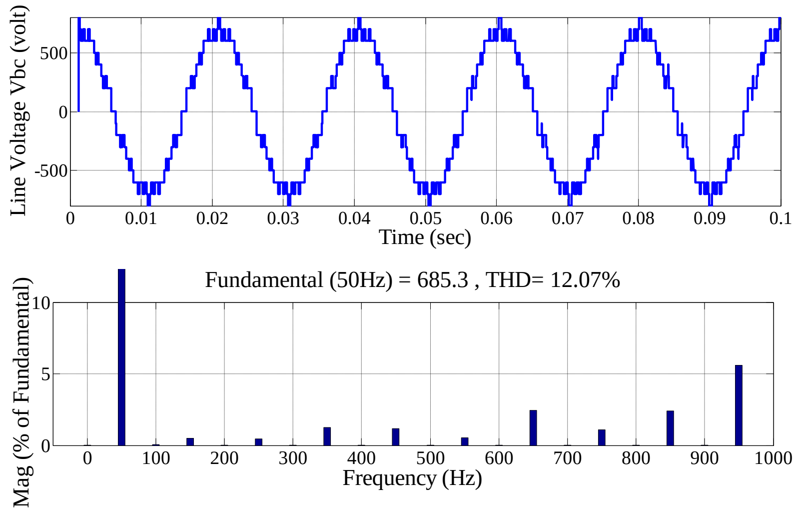


Fig.3.8 (d) Line Voltage and THD of 9-Level Inverter

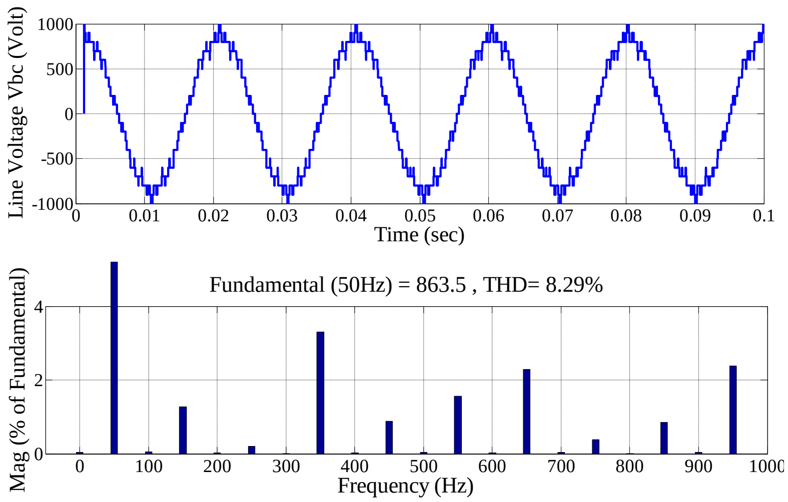


Fig.3.8 (e) Line Voltage and THD of 11-Level Inverter

3.3.2 Output Voltage Waveforms and THD of Cascaded Multilevel Inverters using Phase Shifted Modulation Technique:

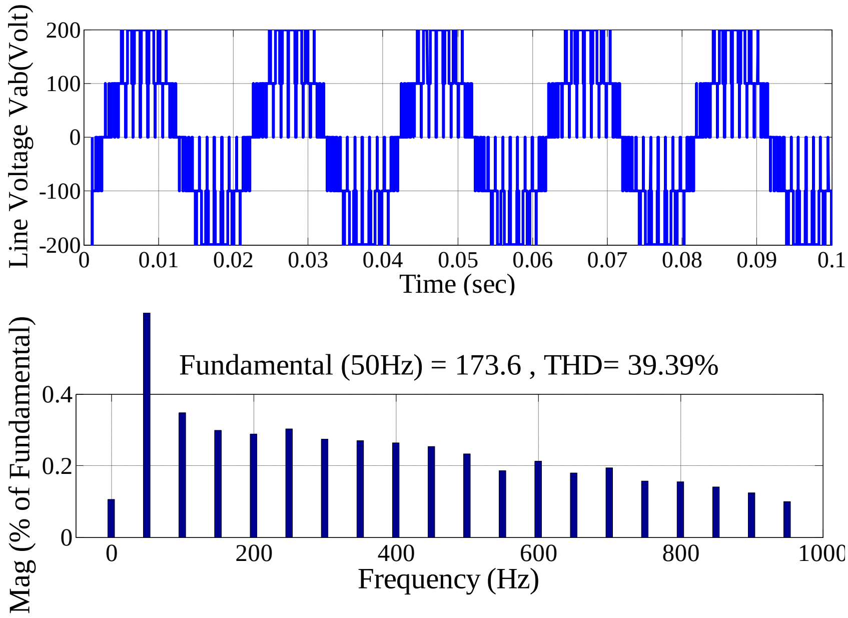


Fig.3.9 (a) Line Voltage and THD of 3-level inverter

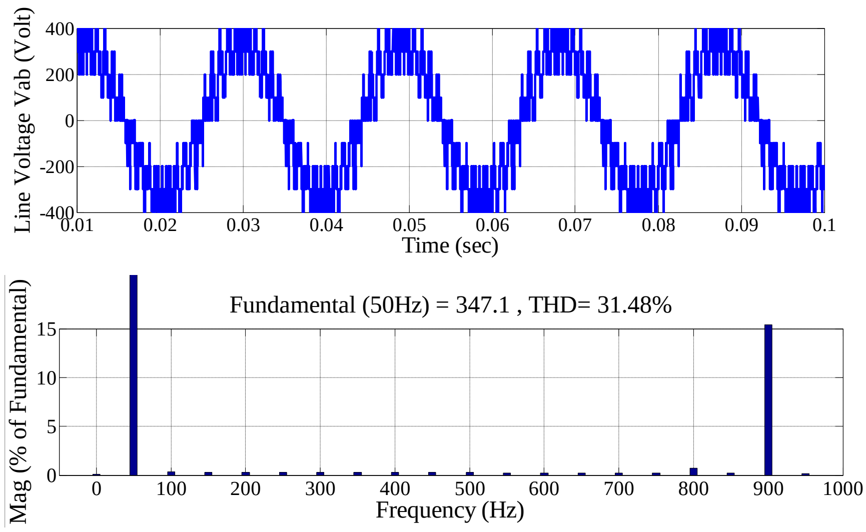


Fig.3.9 (b) Line Voltage and THD of 5-Level Inverter

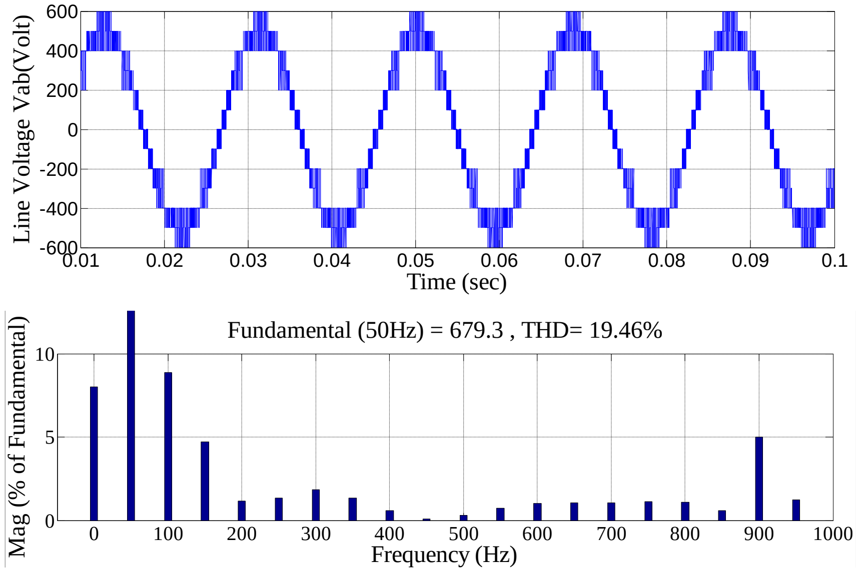


Fig.3.9 (c) Line Voltage and THD of 7-Level Inverter

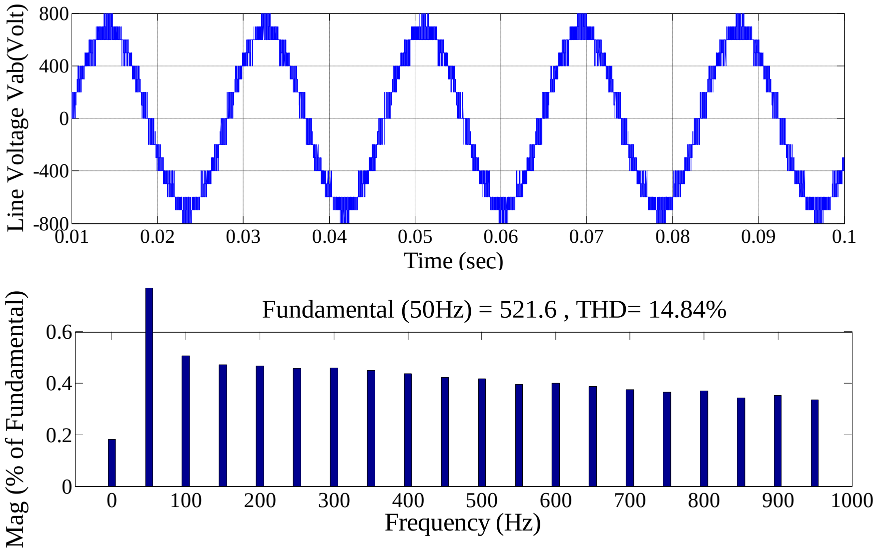


Fig.3.9 (d) Line Voltage and THD of 9-Level Inverter

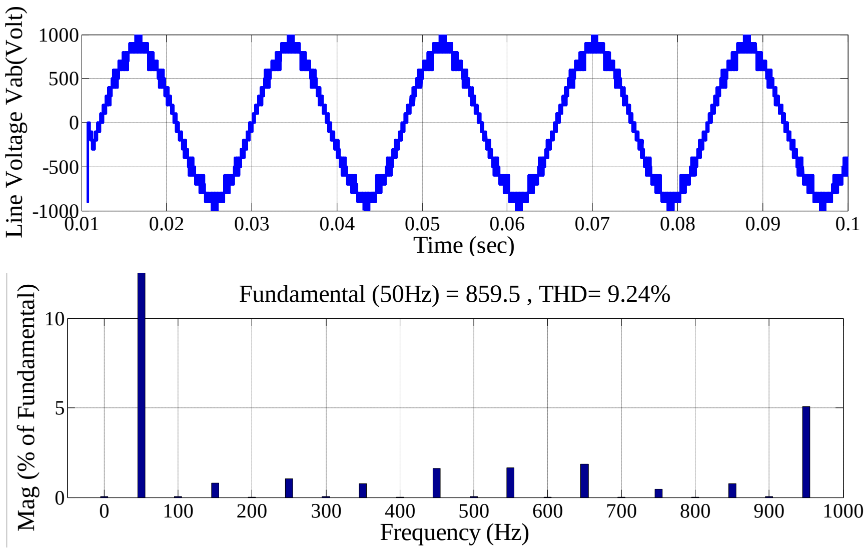


Fig.3.9 (e) Line Voltage and THD of 11-Level Inverter

Table 3.1 Comparison of THD values (in %) of line to line voltage of several cascaded multilevel inverter obtained by implementing carrier based modulation techniques

LINE VOLTAGE LEVEL	LEVEL SHIFTED MODULATION			PHASE SHIFTED MODULATION	REMARK
	IPD	POD	APOD		
3 Level	35.26	40.13	40.13	39.39	IPD Modulation Technique gives better THD
5 Level	18.66	24.68	22.76	31.48	
7 Level	12.05	16.88	16.83	19.46	
9 Level	10.99	12.62	12.07	14.84	
11 Level	6.86	8.87	8.29	9.24	

Table 3.1 shows that IPD modulation technique gives lesser THD for the line–to–line output voltage among different types of multicarrier modulation technique. Hence it is used most frequently in industrial application.

3.4 Selective Harmonic Elimination (SHE) Modulation Technique

SHE PWM is an optimizing algorithm that gives a superior harmonic performance in high power applications with the minimum switching frequency [38, 39]. As compare to other PWM topologies, only the SHE-PWM based techniques work effectively at low switching frequencies and theoretically provide the best output voltage and current quality [2]. However these techniques suffer from a heavy computational process [3]. SHE is normally a two-step digital process. First step of this method is to solve a group of nonlinear equations based on criterion of eliminating selected harmonics at different values of modulation indexes. These equations are solved by a numerical analysis processes or Newton-Raphson methods. Second, the result, which is a set of gating angles typically stored in look-up tables for the gating controller. If the number of the harmonics to be eliminated is increased, the number of pre-calculated switching angles will be increased accordingly; then the look-up table requires very large memory space and therefore the gating data must be carefully set-up.

The multilevel inverter generates a staircase output voltage waveform by switching on and off the switches in the inverters once during one fundamental cycle. This minimizes the switching losses of the devices. Even if the switching frequencies reduce and certain higher order harmonics eliminates, low order harmonics still exists [30, 31]. There are two ways to eliminate low frequency harmonics- i) by increasing the switching frequency in SPWM and SVM in case of two level inverters or in multicarrier based phase shift modulation for multilevel inverters or ii) by computing the switching angles using SHE techniques. The first method is limited by the switching losses and the availability of the voltage steps [30]. Hence, SHE modulation technique can be used for a higher level inverter.

From (2.1), the magnitudes of the Fourier coefficients when normalized with respect to V_{dc} are as follows:

$$H(n) = \frac{4}{\pi n}\left[\cos(n\theta_1) + \cos(n\theta_2) + ... + \cos(n\theta_s)\right] \quad \text{, Where n=1, 3, 5, 7……} \tag{3.1}$$

The switching angles θ_1, θ_2 ... θ_s, can be chosen such that the THD in output voltage is minimum. These switching angles must satisfy the condition: $0 \leq \theta_1 < \theta_2 \ldots < \theta_s \leq (\pi/2)$. Genetic Algorithm (GA), Newton Raphson (NR) methods can be employed for determining these switching angles [47, 48].

For an eleven-level inverter switching angles can be computed to produce the desired fundamental voltage $V_I = m_I(4sV_{dc}/\pi)$. While eliminating 5th, 7th, 11th and 13th harmonics the following equations can be formulated:

$$\cos\theta_1 + \cos\theta_2 + \cos\theta_3 + \cos\theta_4 + \cos\theta_5 = 5m_a \tag{3.2}$$

$$\cos 5\theta_1 + \cos 5\theta_2 + \cos 5\theta_3 + \cos 5\theta_4 + \cos 5\theta_4 = 0 \tag{3.3}$$

$$\cos 7\theta_1 + \cos 7\theta_2 + \cos 7\theta_3 + \cos 7\theta_4 + \cos 7\theta_4 = 0 \qquad (3.4)$$

$$\cos 11\theta_1 + \cos 11\theta_2 + \cos 11\theta_3 + \cos 11\theta_4 + \cos 11\theta_4 = 0 \qquad (3.5)$$

$$\cos 13\theta_1 + \cos 13\theta_2 + \cos 13\theta_3 + \cos 13\theta_4 + \cos 13\theta_4 = 0 \qquad (3.6)$$

Where m_a is modulation index and $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5$ are switching angles.

3.4.1 Algorithm for Newton-Raphson Method to determine the switching angles for an 11-level cascaded Inverter:

1. Initialize the switching angle matrix, all the switching angles should lie within range 0 to $\pi/2$

A= [a_1 , a_2 , a_3 , a_4 , a_5]

2. Calculate the value of:

$$F(a)=F \qquad (3.7)$$

F is the condensed vector format of the following non linear equation system

$$\begin{Bmatrix} Cos(a_1)+Cos(a_2)+Cos(a_3)+Cos(a_4)+Cos(a_5)=5m_a \\ Cos(5a_1)+Cos(5a_2)+Cos(5a_3)+Cos(5a_4)+Cos(5a_5)=0 \\ Cos(7a_1)+Cos(7a_2)+Cos(7a_3)+Cos(7a_4)+Cos(7a_5)=0 \\ Cos(11a_1)+Cos(11a_2)+Cos(11a_3)+Cos(11a_4)+Cos(11a_5)=0 \\ Cos(13a_1)+Cos(13a_2)+Cos(13a_3)+Cos(13a_4)+Cos(13a_5)=0 \end{Bmatrix} \qquad (3.8)$$

Where m_a is the modulation index

3. Linearize the equation (3.8) about a:

$$F + \left[\frac{df}{da}\right] da = H \qquad (3.9)$$

Where, H is the amplitude of the harmonic components.

f is the functions connecting harmonics with switching angles.

and

$$\left[\frac{df}{da}\right] = \begin{bmatrix} \frac{df_1}{da_1} & \frac{df_1}{da_2} & \frac{df_1}{da_3} & \frac{df_1}{da_4} & \frac{df_1}{da_5} \\ \frac{df_2}{da_1} & \frac{df_2}{da_2} & \frac{df_2}{da_3} & \frac{df_2}{da_4} & \frac{df_2}{da_5} \\ \frac{df_3}{da_1} & \frac{df_3}{da_2} & \frac{df_3}{da_3} & \frac{df_3}{da_4} & \frac{df_3}{da_5} \\ \frac{df_4}{da_1} & \frac{df_4}{da_2} & \frac{df_4}{da_3} & \frac{df_4}{da_4} & \frac{df_4}{da_5} \\ \frac{df_5}{da_1} & \frac{df_5}{da_2} & \frac{df_5}{da_3} & \frac{df_5}{da_4} & \frac{df_5}{da_5} \end{bmatrix}$$

$$da = \begin{bmatrix} da_1 & da_2 & da_3 & da_4 & da_5 \end{bmatrix}$$

4. Solve *da* from equation (3.7) by:

$$da = (H - F) INV \left[\frac{df}{da} \right] \tag{3.10}$$

Where,

$INV\left[\frac{df}{da} \right]$, is the inverse matrix of $\left[\frac{df}{da} \right]$

5. Change the initial values of each step by:

$$a(n+1) = a + da \tag{3.11}$$

6. Repeat the process, equation (3.7) to equation (3.11) until *da* satisfied the desired degree of accuracy.

The major problem of Newton Raphson's method is the knowledge of starting points of switching angles .By applying Newton Raphson's Method according to the above algorithm, switching angles were computed as θ_1=6.57°, θ_2=18.94°, θ_3=27.18°, θ_4=45.14°, θ_5=62.24°.

If the inverter output is symmetrically switched during the positive half cycle of the fundamental voltage to +V_{dc} at 6.57°, +2V_{dc} at 18.94°, +3V_{dc} at 27.18°, +4V_{dc} at 45.14°, and +5V_{dc} at 62.24°, and similarly In the negative half cycle to –V_{dc} at 186.57°, –2V_{dc} at 198.94o,–3V_{dc} at 207.18°, –4V_{dc} at 225.14° and –5V_{dc} at 242.24°, the output voltage of 11-level inverter will not contain the 5th, 7th, 11th and 13th harmonic components.

3.5 Results of 11-level Cascaded H-bridge Inverters using SHE Modulation Technique

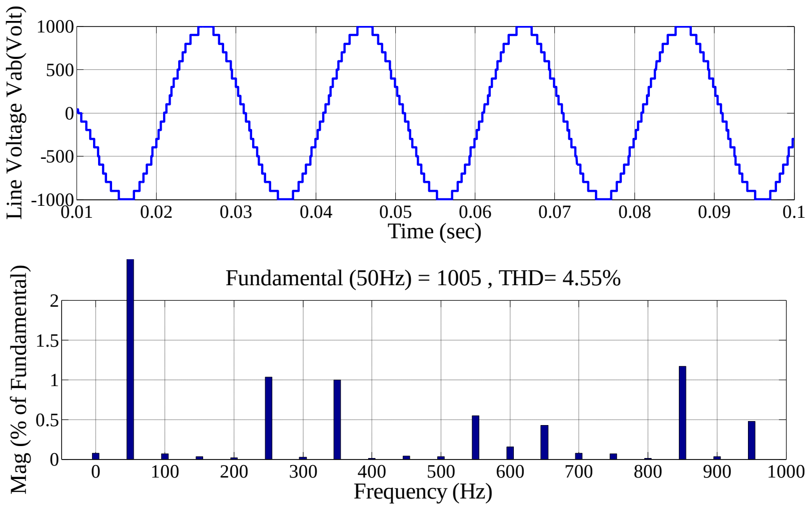


Fig.3.10 Line Voltage and THD of 11-Level Inverter with SHE Modulation

It was found that SHE modulation Technique resulted in reduced THD than multicarrier modulation Techniques. Hence, SHE modulation technique was implemented for cascaded rectifier inverter configuration.

3.6. Cascaded Rectifier Inverter configuration (ac-dc-ac converter)

Figure.15 shows the output voltage waveform of 11-level rectifier inverter set using SHE modulation technique.

3.7 Result of Rectifier Inverter configuration with SHE modulation technique

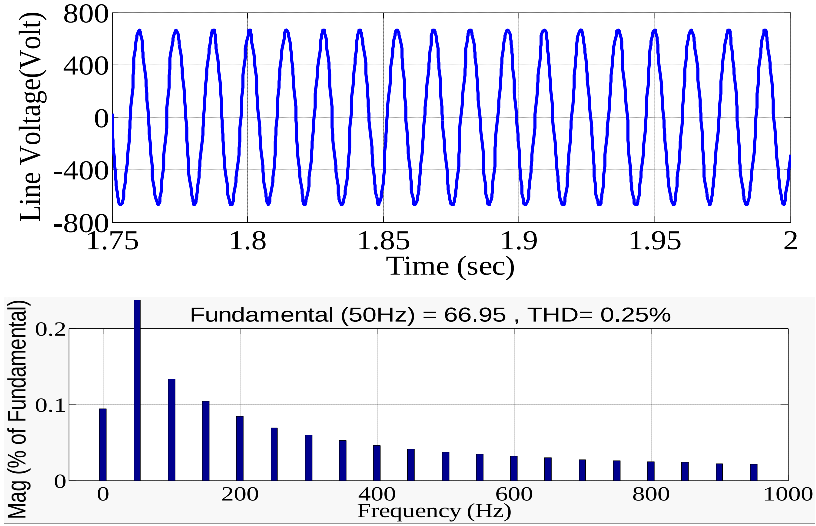


Fig.3.11 Line Voltage and THD of 11-Level Rectifier Inverter configuration

By using SHE modulation technique for cascade rectifier inverter configuration, THD was found to be 0.25% as shown in the Fig.3.11. Hence, the SHE technique was implemented in the cascaded eleven-level inverter in the electric traction drive.

3.8 Summary

In this chapter, different multicarrier modulation techniques were implemented in 3-level, 5-level, 7-level, 9-level and 11-level cascaded H-bridge inverter. Line-line voltage waveforms and their THDs were shown. It was proved that with increase in level, steps in output voltage waveform increases and it seems more likely to as sinusoidal waveform. Again, with increase in level THD decreases. It was found that among all the multicarrier sinusoidal modulation techniques IPD modulation has lower THD. Here, THD of 11-level inverter is less than the other lower level inverters. To reduce switching frequency, SHE modulation technique was implemented in 11-level cascaded H-bridge inverter. In SHE modulation technique, switching angles were calculated offline and given to the switches. THD of 11-level cascaded H-bridge inverter was found to be less than 5% and THD of 11-level cascaded rectifier-inverter set was found to be 0.25%. Hence, SHE modulation technique was employed in traction system model.

CHAPTER 4

4. ELECTRIC TRACTION DRIVES

4.1. Introduction

An electric locomotive is powered by electricity from overhead lines, a third rail or on-board energy storage such as a battery or fuel cell. Electric locomotives with on-board fuelled prime movers, such as diesel engines or gas turbines, are called as diesel-electric or gas turbine-electric locomotives because the electric generator/motor combination serves only as a power transmission system. A railway electrification system supplies electrical energy to railway locomotives and multiple units so that they can operate without having an on-board prime mover. There are several different electrification systems in use throughout the world.

The first known electric locomotive was built in 1837 by chemist Robert Davidson of Aberdeen. It was powered by galvanic cells (batteries).The first successful application of electric traction was in 1879, when an electric locomotive ran at an exhibition in Berlin. The first commercial applications of electric traction were for suburban or metropolitan railroads. One of the earliest electric locomotives came in 1895. In order to avoid smoke and noise problems in a tunnel the Baltimore and Ohio electrified a stretch of track.

Electric drive technology was progressively changed from DC motor drive with rheostat control to induction motor drive with inverter control especially in early 1990s. Railway Company could save maintenance cost of rolling stock by half after introduction of the new technology. In large cities where transport density is relatively high, energy consumption of commuter trains also reduced drastically by regenerative brake in place of mechanical brake and by train weight reduction. As far as commuter multiple units are concerned, the three phase drives with one inverter feed several traction motors in parallel, say multiple motor drive, is much less expensive than ones of individual motor drive. This solution will be applied to more railway vehicles in future. If railway vehicle has possibility to make railway operation more efficient, one can use electrical brake that can minimize vehicle maintenance staffs and simplifies train operation. Introducing this technology, all brake force from the top speed to zero is generated electrically and there is no mechanical wear of brake materials.

Some remarkable features of electric traction system:

1. It is the cleanest form of drive.
2. It has high starting torque.
3. It requires less maintenance.
4. No coal and water required and hence saves money.

5. It enables quicker acceleration.
6. It does not consume time to start.
7. It has high power to weight ratio.
8. Smooth braking is possible with electric braking
9. Railway electrification leads to rural electrification which is the most important industrial development.

Limitations of electric traction system:

1. High capital cost is required for electrification
2. Power failure can affect the railway system.
3. There is problem of electromagnetic interference due to the presence of both the communication lines and power lines.

4.2 Railway Electric Traction Drive

At the end of the nineteenth century, railway electrification emerged as a means of traction. The advent of power electronics concept has proved to a blessing in the field of traction system. It supplies the energy of the catenaries to traction motors in a controlled manner.

There are mainly three types of traction units. These are:

1. DC traction units: these units draw Direct Current from either a conductor rail or an overhead line.
2. AC traction units: these draw alternating current from an overhead line.
3. Multi-system unit: These units operate under several different voltages and current types.

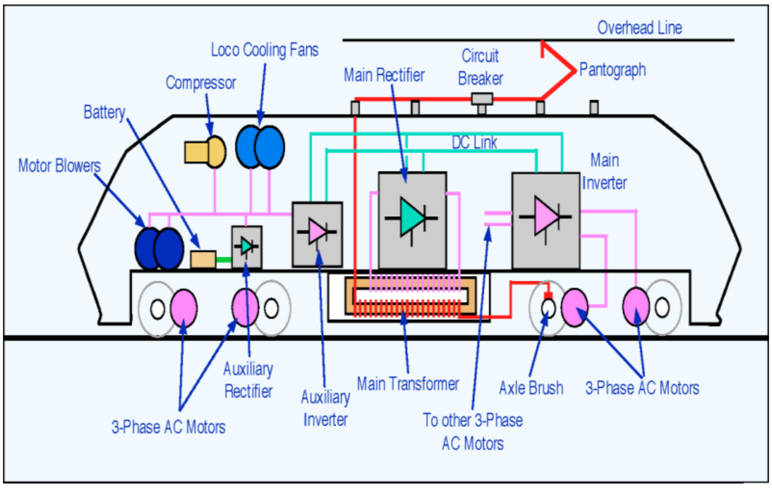


Fig.4.1 Schematic layout of an Electric Locomotive

Fig.4.1 shows the schematic layout of an electric locomotive.

4.3 Tractive Effort:

There are mainly three types of traction units. These are:

1. DC traction units: these units draw Direct Current from either a conductor rail or an overhead line.
2. AC traction units: these draw alternating current from an overhead line.
3. Multi-system unit: These units operate under several different voltages and current types.

4.4 Electric Braking while Stopping

In order to stop the traction motor, supply is cut-off from the motor. When the supply is cut off from the motors, the speed decrease and gradually come to rest. So in order to bring the motor to rest quickly, brakes has to be applied. Brakes can be either mechanical or electrical brakes. Because of the frequent wear of the mechanical brakes, high maintenance is required. To avoid this, electrical braking is done to have smooth and quick braking with low maintenance cost.The function of braking is to provide means to dissipate the stored kinetic energy of the combined motor-system inertia during the period of deceleration from a higher to a lower, or zero speed. The dissipation of kinetic energy may be external to the windings (external braking) or within them (internal braking). Sometimes a combination of internal and external braking may be employed to optimize braking performance. External braking uses a form of mechanical brake that is coupled to the motor. It can be used for all types of motors and requires special mechanical coupling. Methods for producing internal braking can be divided into two groups: counter-torque (plugging) and generating (dynamic and regenerative braking). In the counter-torque group, torque is developed to rotate the rotor in the opposite direction to that which existed before braking. In the generating group, torque is developed from the rotor speed. Dynamic torque is developed by motor speeds that are less than the synchronous speed, and energy is dissipated within the motor or in a connected load. Developed torque is zero at zero rotor speed.

The energy put into accelerating a train and into moving it uphill is "stored" in the train as kinetic energy. When brake is applied, this stored kinetic energy of the motor is dissipated through braking resistor (dynamic braking) or fed back to the supply (regenerative braking) while moving it downhill. Dynamic braking is a process in which kinetic energy of rotor is dissipated in external resistor as heat energy. It is an electrical braking process used in many industrial applications. Dynamic braking allows sudden stop of electrical motor without mechanical wear and tear.

There are three types of electrical braking: plugging, DC dynamic and regenerative braking. Plugging in induction motor occurs when any of the two stator phases are reversed. The direction of the rotating field reverses. The direction of the rotor and stator are opposite in nature and the slip is greater than unity.An induction motor operates in the, plugging mode for slips higher than one and is obtained when the rotor rotate in the reverse direction. Since the relative speed between the rotating field and the rotor remains positive, the motor torque is positive and the motor draws power from the source. Since the motor is running in the reverse direction, a positive torque provides the braking operation. The electrical power generated by the conversion of mechanical power supplied by the load, inertia and also the power supplied by the source, are dissipated in the motor circuit resistances. Thus, this method is a highly inefficient method of braking [39].

Dynamic braking is a process in which kinetic energy of rotor is dissipated in external resistor as heat energy. It is an electrical braking process used in many industrial applications. Dynamic braking allows sudden stop of electrical motor without mechanical wear and tear. In dynamic braking, stator has no supply at the time of braking. However, rotor is rotating due to inertia. When stator has no supply and rotor is rotating, this flux induces voltage in stator. In other words, motor is acting as generator and rotors kinetic energy is now transferred to stator as electrical energy. If we can just arrange a system that dissipates this energy, we actually can devise a dynamic braking. However, if a DC current is passed through the stator, a steady flux will be generated in the air gap and the rotation of the short circuited rotor in this flux produces an electromagnetic force (emf). Thus, a sufficient current is produced for the braking torque. This process is also called capacitive braking since capacitor is used in braking.

The energy generated in the dynamic braking mode is transferred to the resistors, called as braking resistors which are generally mounted on the locomotive housing. Hence, the energy of the rotor is dissipated through the braking resistors in the form of heat. In order to use this energy regenerative braking can be employed. This is the more energy-effective braking type in which power is given back to the catenary power system. This power from the catenary is either be used by another electric train or returned to the power system. It is seen that more than 25% of the total power used for traction can be returned to the catenary power system. When the locomotive is moving up the slope, the traction motor operates in motoring mode. In this mode motor (rotor) speed is less than the synchronous speed. When the load moment changes or the locomotive is moving down the slope, electric brakes are applied to lower the motor speed or to bring the locomotive to rest. The armature current is reversed and electromagnetic braking moment is developed. While electromagnetic moment, which is a counter torque with respect to the armature becomes a braking moment is called regenerative mode. In regenerative mode the power produced by the generator is given to the catenary or used for battery charging.

4.5 Electric Traction Drive with Braking

A) Capacitive Braking

In capacitive braking, stator is disconnected from supply at the time of braking. However, rotor is rotating due to inertia of the load. A capacitor bank is connected with the stator which will store the energy which comes from rotor magnetic field. Now, if we connect a three-phase resistor bank across the stator, this energy will be dissipated through it in the form of heat. Hence rotor losses its kinetic energy more rapidly and brake is experienced [44]. This process is called capacitive braking since capacitor is used in braking process.

B) DC injection Braking

In DC injection braking, motor is disconnected from the supply, motor will be rotating due to inertia, and a zero frequency current is fed to the stator by connecting a DC supply to it which will produce zero air-gap power. By applying the DC voltage to the stator winding of an induction motor across two of the three stator leads, the induction motor becomes an inverted (or inside-out) synchronous generator, for which the stator now becomes the field and the rotor of the induction motor becomes a rotating armature [45]. At standstill, the rotor current and braking torque become zero. DC braking is suitable only for stopping the motor and its braking torque is small at high speed.

C) Combination of Capacitive and DC injection Braking

The combination of capacitor and DC injection braking will be more effective than individual braking. Fig.4.2 shows the block diagram of electric traction drive with combination of capacitive and DC injection braking. 11-level cascaded H-bridge rectifier-inverter set is used for controlling the power input to the motors. At 5 sec stator is disconnected from the supply and capacitor bank is applied by using switch set-1 and switch set-3 respectively to store the kinetic energy of the rotor as rotor is still rotating. The capacitive braking is applied at high speed, the speed of the motor will be reduced to 50% - 70% of the full speed and then DC injection braking is applied at 6 sec by using switch set-2. The DC injection braking is applied to produce a high negative torque to bring the motor to standstill in few seconds. At standstill motor speed, torque and rotor current will be zero.

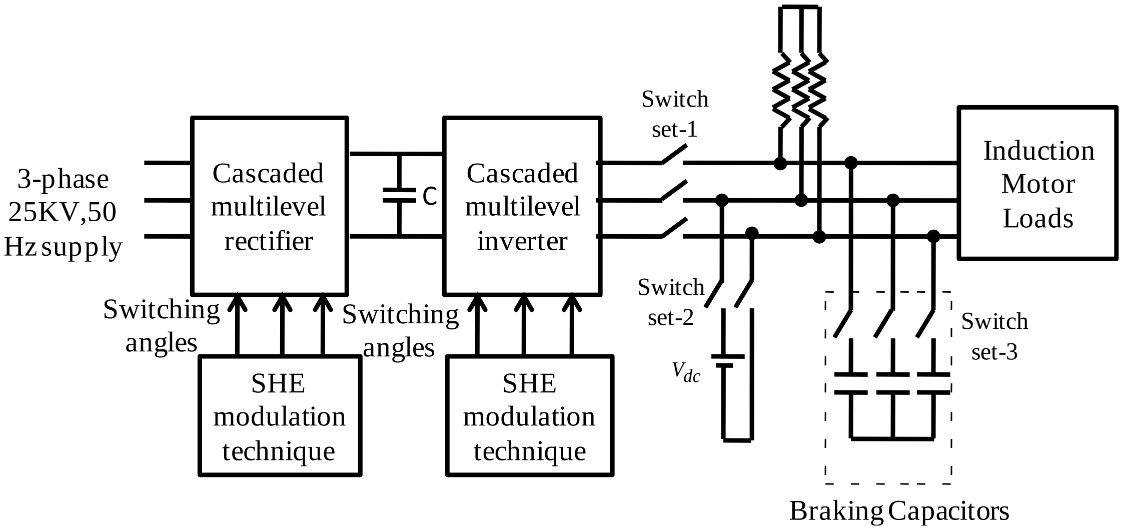


Fig.4.2 Block Diagram of Electric Traction Drive with DC dynamic Braking

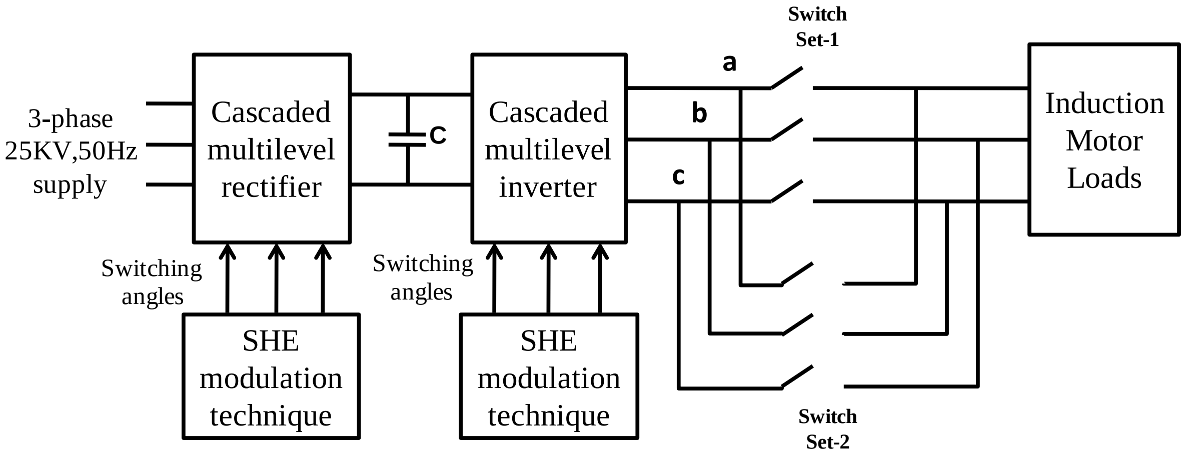


Fig.4.3 Block Diagram of Electric Traction Drive with Plugging

4.6 Simulation Results

By using MATLAB/SIMULINK environment, a simulation model of IGBT based 11-level cascaded multilevel inverter drive using SHE modulation technique, for electric railway traction has been implemented. Combination of capacitive and DC injection braking and plugging were employed for braking purpose. During the application of first type of braking, at 5 sec stator is disconnected from the supply and a capacitor bank was connected with the stator, at 6 sec DC voltage was connected across two of the three stator leads in order to bring the speed of the motor to zero in few seconds. Plugging is used when sudden braking is required. Fig.4.3 shows the block diagram of electric traction drive with plugging. Here, it was done by disconnecting the motor from the supply using switch set-1 and connecting the motor with supply by interchanging the phase-a and phase-b at 5 sec by using switch set-2. Hence a high negative torque was produced to sop the motor quickly.

A) Using a Combination of Capacitive and DC Injection Braking

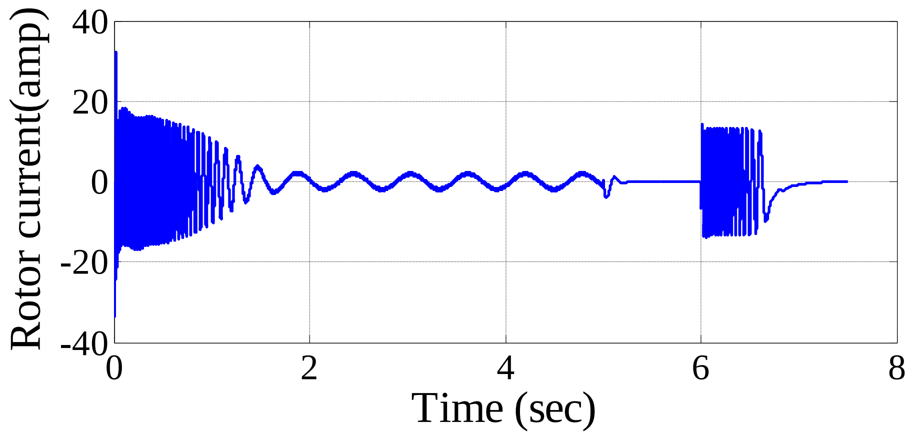


Fig.4.4 Rotor current of induction motor

Fig.4.4 shows the rotor current waveform of each of the induction motor. At 5 sec (when supply is disconnected), rotor current becomes zero, again at 6 sec (when DC voltage is applied across the stator) current will be induced on rotor. This will go to zero when speed goes to zero. Fig.4.5 shows the stator current across induction motor. From this curve it is clearly visible that stator current becomes zero when supply is disconnected at 5 sec. At 6 sec, a DC current is allowed to flow by applying a DC voltage across the two terminal of the stator.

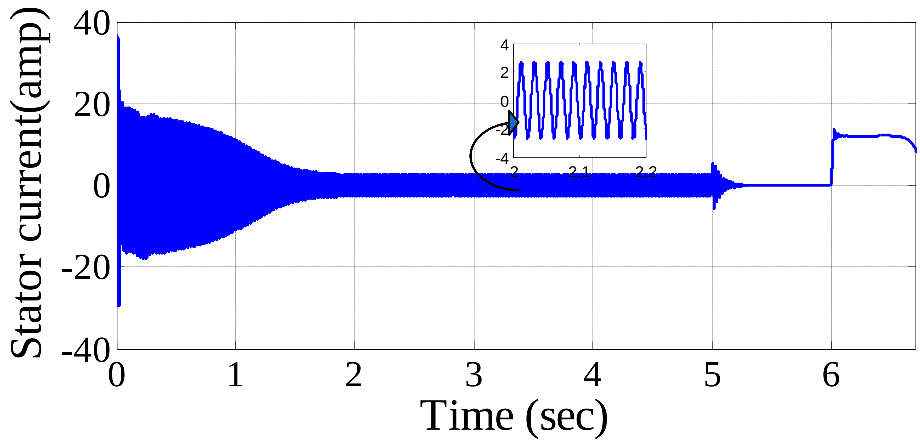


Fig.4.5 Stator current of induction motor

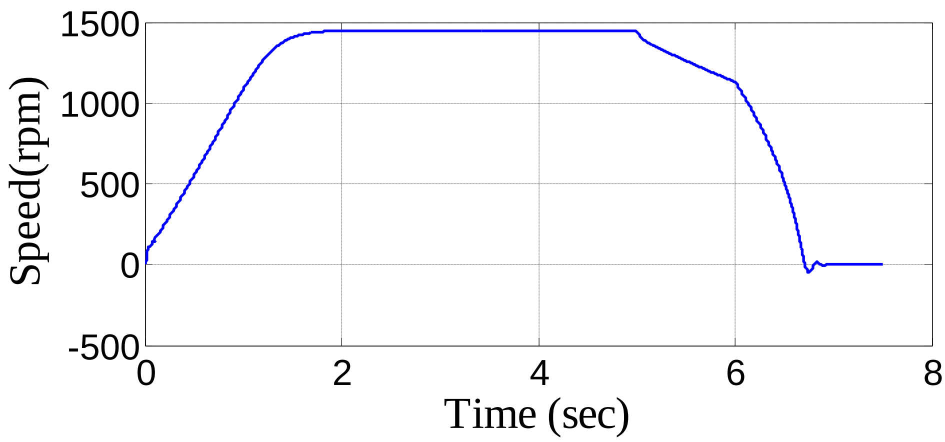


Fig.4.6 Speed-Time curve of induction motor

Fig.4.6 shows the speed-time curve of each of the induction motor. This shows, from 0 to 1.8 sec, speed is increasing linearly. In this region the speed-time curve is straight line. This region shows the constant acceleration period of the motor. From 1.8 sec to 5 sec, motor is running at constant speed. This region is called the free running period of the motor. From 5 sec to 6 sec, supply is cut-off from the motor and the speed of the train gradually decreases because of its own resistance. This period is known as coasting period of motor. After coasting period, braking is applied to bring the motor to rest. The period from 6 sec to 6.5 sec, is known as braking period. Fig.4.7 shows the torque developed by each of the induction motor. At starting, torque is high. At braking period (6 sec to 6.5 sec) a high negative torque is developed. Fig.4.8 and 4.9 shows the rms current and voltage applied to the motor respectively. From Fig.4.9, it can be shown that by using 11-level cascaded H-bridge rectifier inverter set a three-phase, 25kV, 50Hz supply of the catenary voltage is stepped down to three-phase, 400V, 50 Hz to be used by the traction motors. When supply is cut-off (at 5 sec) voltage goes to zero and during braking a DC supply of 200 V is applied across the stator.

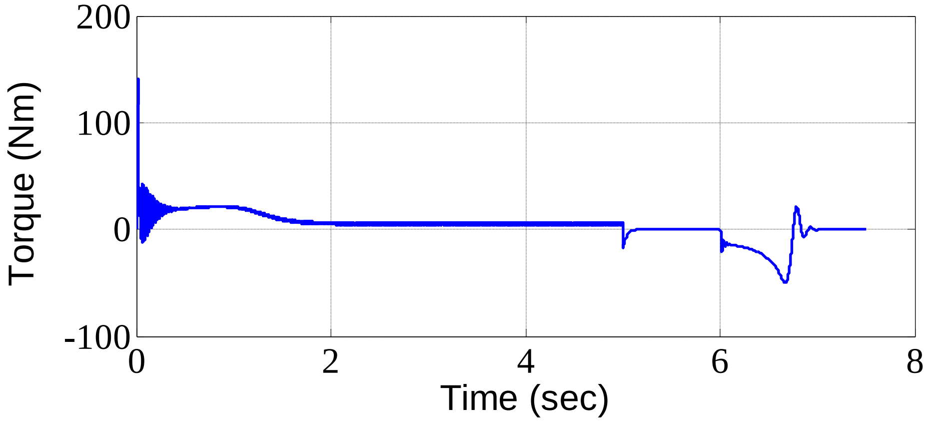


Fig.4.7 Torque developed by induction motor

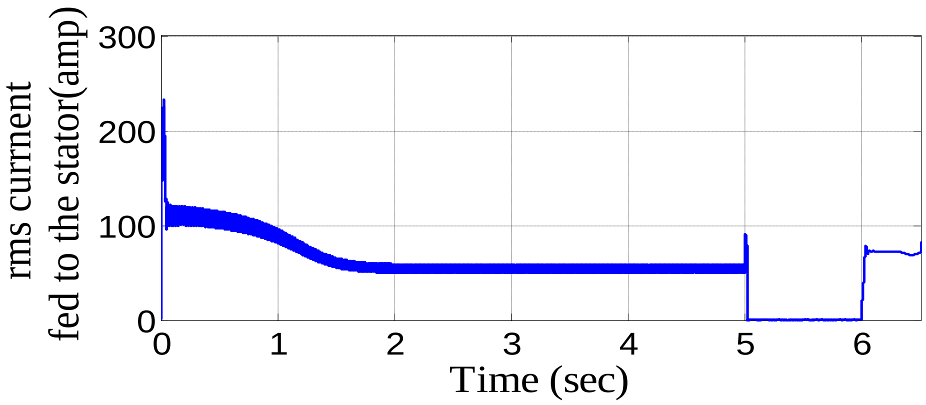


Fig.4.8 Rms current fed to the induction motor

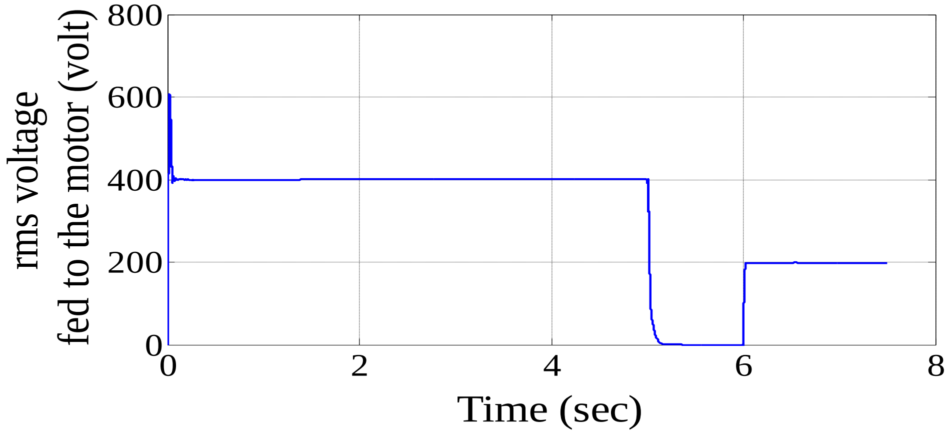


Fig.4.9 Rms voltage fed to the induction motor

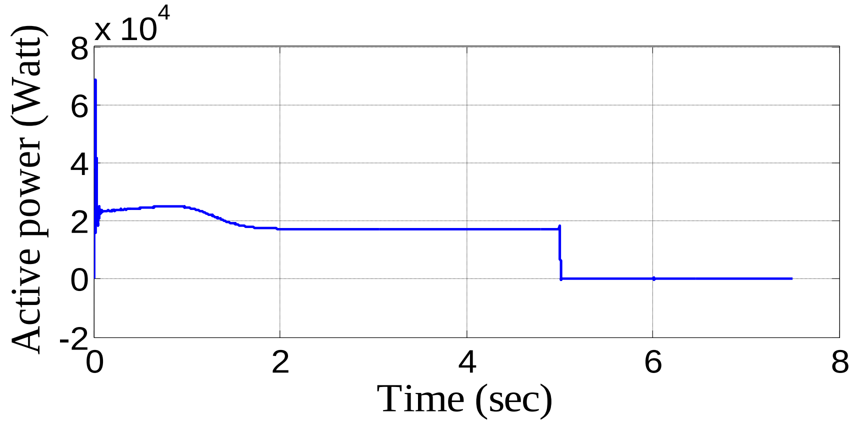


Fig.4.10 Active Power Consumption of induction motor

Fig 4.10 and Fig.4.11 shows the active and reactive power consumed by the motor respectively. The active and reactive power consumed by the motor during removal of supply (at 5 sec) from the motor can be seen Fig.4.12 and Fig.4.13 respectively.

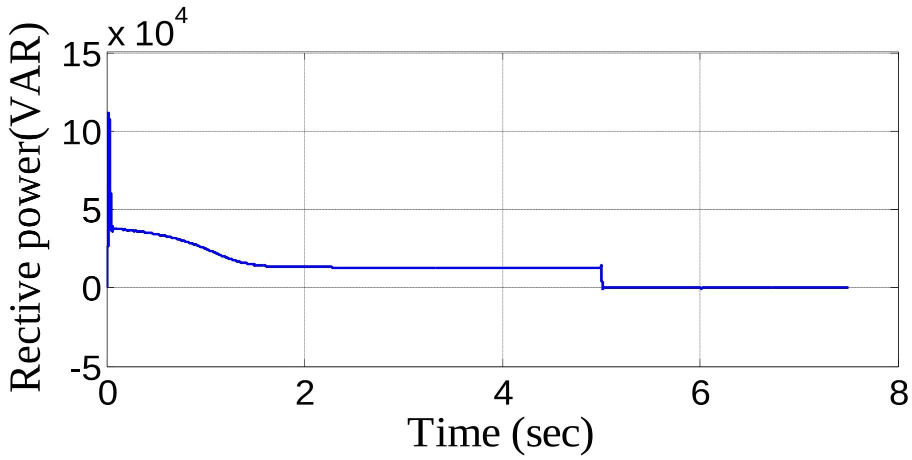


Fig.4.11 Reactive Power Consumption of induction motor

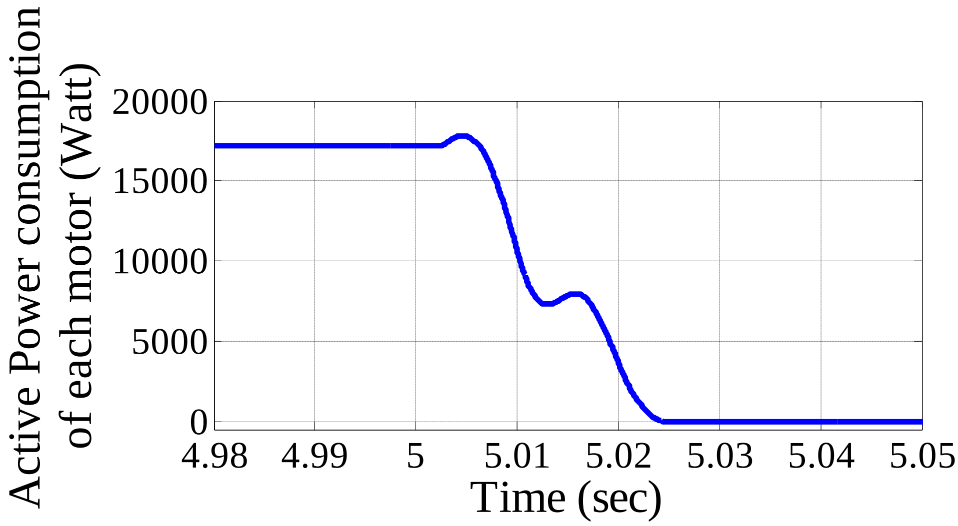


Fig.4.12 Active Power Consumption at the instant supply is removed from the motor

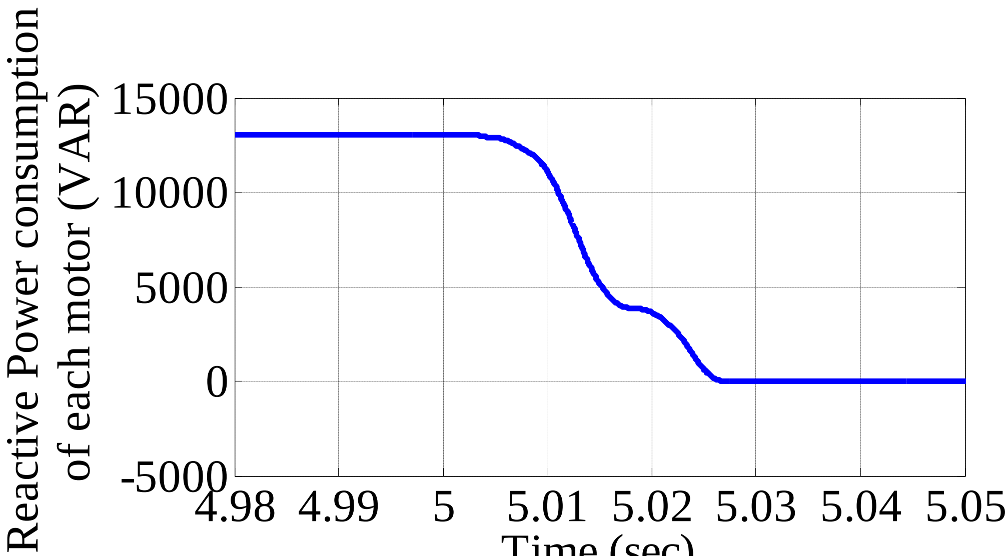


Fig.4.13 Reactive Power Consumption at the instant supply is removed from the motor

B) Results Using Plugging

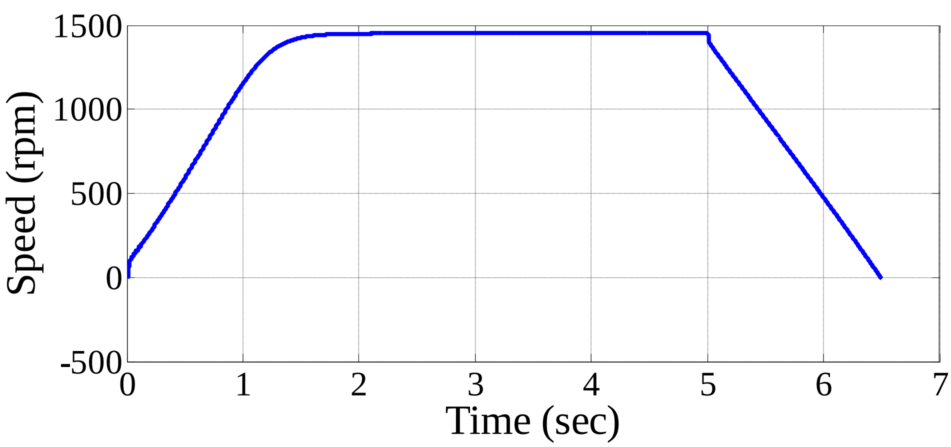


Fig.4.14 Speed-Time curve of induction motor

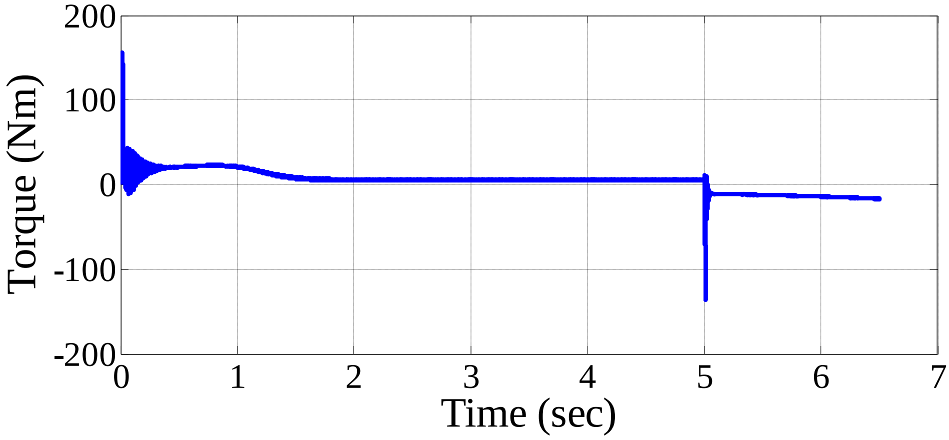


Fig.4.15 Developed torque of induction motor

Fig.4.14 and Fig.4.15 shows the speed-time curve and torque developed by induction motor when plugging was applied at 5 sec.

4.7Summary

By using MATLAB/SIMULINK environment, a simulation model of IGBT based 11-level cascaded multilevel inverter drive using SHE modulation technique, for electric railway traction has been implemented. It was found that the cascaded multilevel rectifier and inverter can be used in the traction drive of the railway system. It can step down the supply voltage to the rated voltage (400V) of the Induction motor. Hence, it eliminates the need of the bulky transformer. Different braking methods like plugging and DC dynamic braking were implemented. Plugging generates high amount of heat which may burn the motor windings, hence, this braking scheme shouldn't be used frequently for braking of induction motor. Again, in case of plugging motor should be disconnected from the supply when motor speed comes to zero to avoid excess heating of rotor bars.

CHAPTER 5

5. SPEED CONTROL OF TRACTION MOTOR

5.1 Introduction

Speed of the induction motor can be controlled by using scalar control, vector control, direct torque and flux control and adaptive control. Here, a scalar control and advanced vector control method is employed for induction motor drive. Closed loop speed control with V/f control and slip regulation, and speed control with direct torque and flux control are studied. Scalar control, as the name indicates, is due to magnitude variation of control variables only and disregards the coupling effect in the machine. For example, to control the flux the voltage of a machine can be controlled, and to control the torque frequency or slip can be controlled. However, flux and torque are also the function of frequency and voltage, respectively. Scalar control technique is somewhat simple to implement, but the inherent coupling effect between torque and flux gives sluggish response and the system is easily prone to instability because of a high-order system effect. To get fast response vector or field oriented control is adapted. In the beginning of 1970s vector control method is invented.

A static converter which delivers variable-frequency power to a motor must also vary the terminal voltage as a function of frequency in order to maintain the proper magnetic conditions in the core. The applied voltage/frequency ratio must be constant in order to maintain constant flux, and this mode of operation is known as constant V/f. This open-loop operation of an induction motor at variable frequency provides a satisfactory variable-speed drive when the motor is required to operate at steady speeds for long periods. When the drive has to deal with rapid acceleration and deceleration command, an open-loop system gives unsatisfactory result, since the supply frequency cannot be varied very quickly. In order to get a fast dynamic response, closed-loop feedback control methods are essential.

5.2 V/f Control Theory

The base speed of the induction motor is directly proportional to the supply frequency and the number of poles of the motor. Since the number of poles is fixed by design, the best way to vary the speed of the induction motor is by varying the supply frequency. The torque developed by the motor is directly proportional to the magnetic field produced by the stator. So the voltage applied to the stator is directly proportional to the product of the stator flux and angular velocity. This makes the flux produced by the stator proportional to the ratio of applied voltage and frequency of supply. By varying the frequency, the speed of the motor can be varied. Therefore, by varying the voltage and frequency by the same ratio, flux and hence the torque can be kept constant throughout the speed range. This makes constant V/f the most common speed control of the induction motor. Fig.5.1 shows the speed-torque characteristic of induction motor with V/f control.

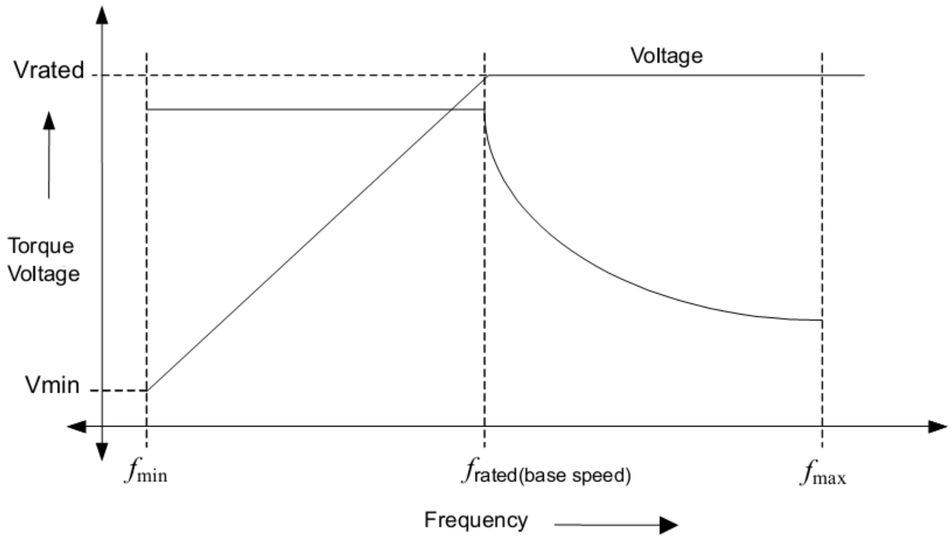


Fig.5.1 Speed-Torque characteristic of V/f control

1. The stable operating region of the motor is increased. Instead of simply running at its base rated speed, the motor can be typically from 5% of the synchronous speed up to the base speed .The torque generated by the motor can be kept constant throughout this region.
2. At the base speed, the voltage and frequency reach the rated values. To drive the motor beyond the base speed, we have to increase the frequency further. However, the applied voltage cannot be increased beyond the rated voltage. Therefore, only the frequency can be increased, which results in the reduction of torque. Above the speed the factors governing torque become complex.
3. The acceleration and deceleration of the motor can be controlled by controlling the change of the supply frequency to the motor with respect to time.

The induction motor draws the rated current and delivers the rated torque at the base speed. When the load increases, the speed drops and slip increases. The motor can take up to 2.5 times rated torque with around 20% drop in speed. Any further increase of load on the shaft can stall the motor.

Fig.5.2 shows the block diagram of close loop speed control with V/f control and slip regulation. Here, sinusoidal PWM inverter is used because it can provide the constant volts/hertz supply required for constant-torque operation of an ac motor. An L-C filter is interposed between the rectifier and the inverter to maintain a ripple free dc voltage at the input of the inverter, and thus prevent the harmonics in the rectifier output voltage from getting coupled with the inverter. Here conventional three-phase two-level inverter is used.

The voltage source inverter producing output voltage or a current with levels either zero or $\pm V_{dc}$, are known as two level inverter. A quality output voltage or a current waveform with a minimum amount of ripple content can be obtained with high switching frequency along with various PWM strategies. In high power and high-voltage applications, these two-level inverters have some limitations in operating at high frequency mainly due to switching losses and constraints of device rating. The dc link voltage of a two-level inverter is limited by voltage ratings of switching devices. In addition, the two level inverters generate high frequency common-mode voltage within the motor windings which may result in motor and drive application problems. In order to reduce the harmonic content in the voltage, to be supplied to the motor, multilevel structure can be adapted. Again, in the conventional technique normal PWM method is used. So that the voltage and current are of poor qualities and the switching frequency causes more amount of switching losses. Those drawbacks are rectified using multilevel inverter. The voltage and current quality are better and the switching losses are reduced when compared to the conventional technique and also, the THD is found to be better as shown in chapter 3.Here, 11-level cascaded H-bridge inverter is used which can be used for traction system. In Phase Disposition (IPD) modulation technique is used to reduce the harmonic contents in the voltage to be fed to the motor.

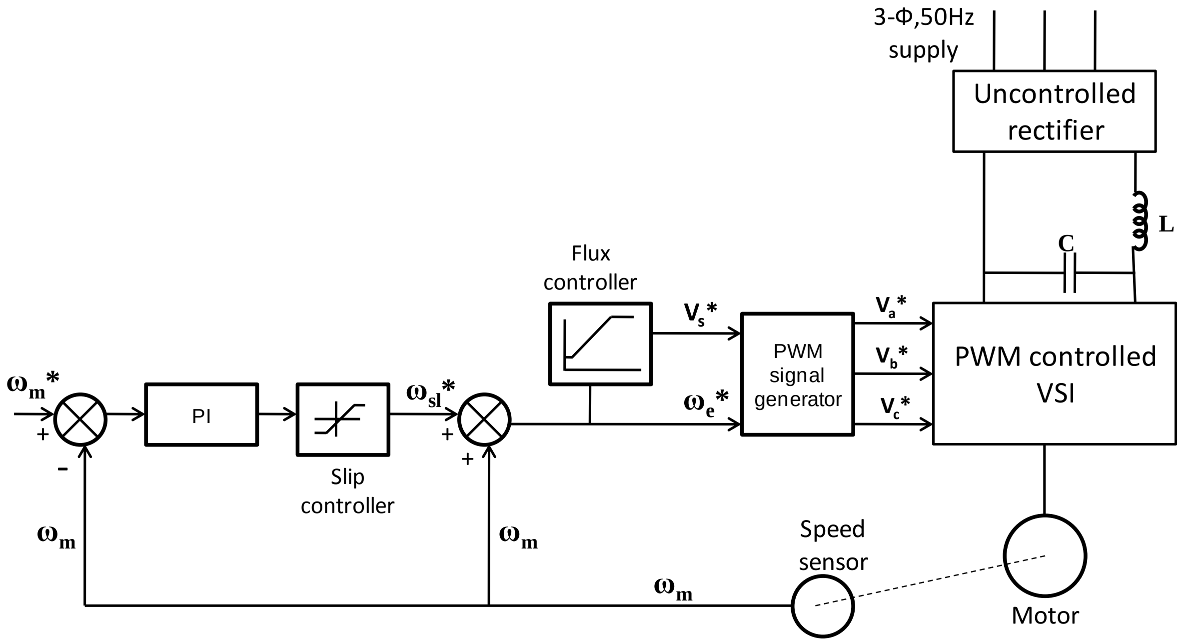


Fig.5.2 Block Diagram of Closed loop Speed Control of Traction Motor using V/f control and slip regulation

5.3 Simulation Results

By using MATLAB/SIMULINK environment, a simulation model of closed loop speed control of traction motor using V/f control and slip regulation has been implemented. Here voltage and frequency are controlled in order to maintain a constant ratio. Frequency is controlled by controlling the speed. Speed error is generated from reference speed and actual speed of the motor. PI controller is used to track the reference speed.

A) Results Using two-level inverter

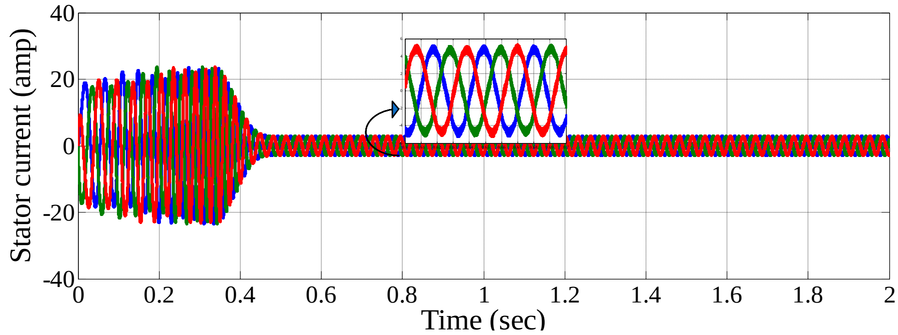


Fig.5.3 Stator current of motor

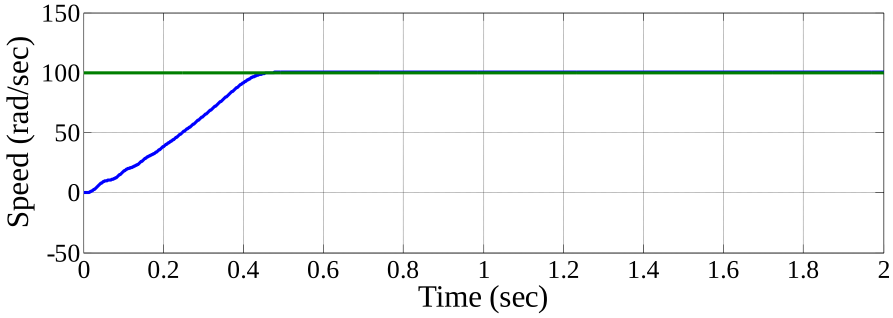


Fig.5.4 Speed-Time Curve of Induction Motor

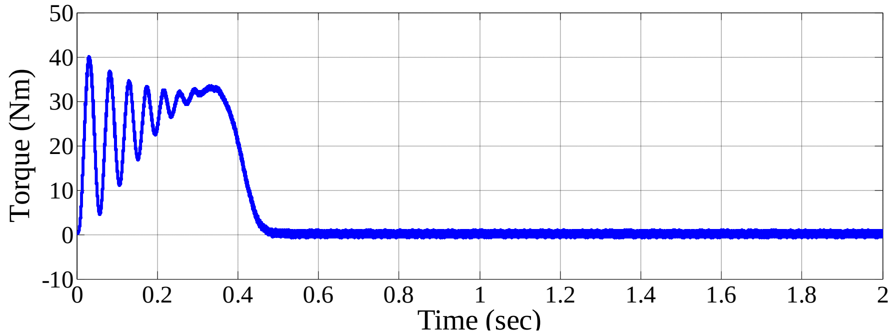


Fig.5.5 Developed Torque

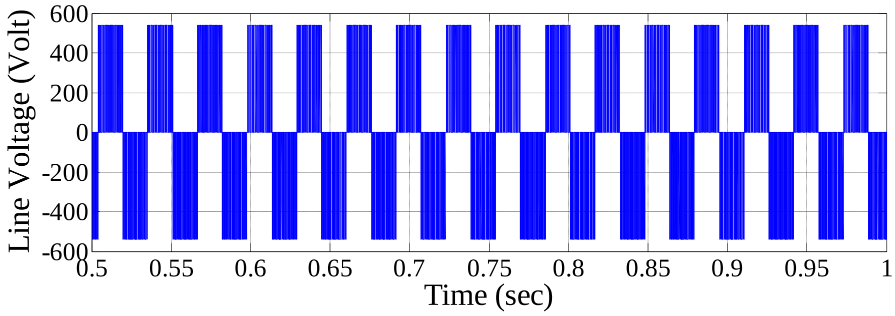


Fig.5.6 Line voltage fed to the motor

Fig.5.3, Fig.5.4 and Fig.5.5 show the waveforms of stator current, speed time curve and developed torque respectively. Reference speed was set at 100 rad/sec. Fig.5.6 shows the line voltage fed to the induction motor with two-level inverter.

B) Results with Load Variation

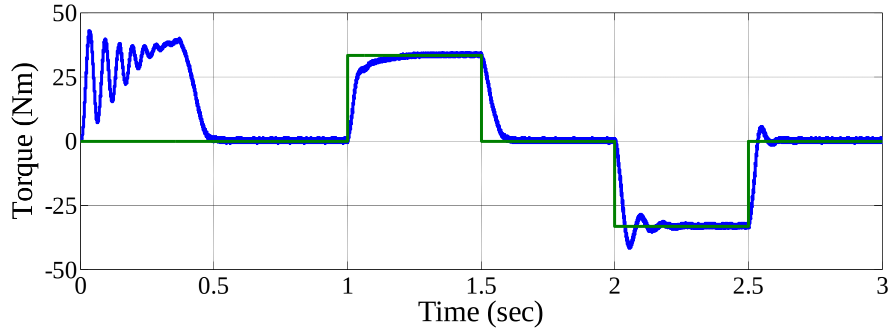


Fig.5.7 Load Torque and Developed Torque

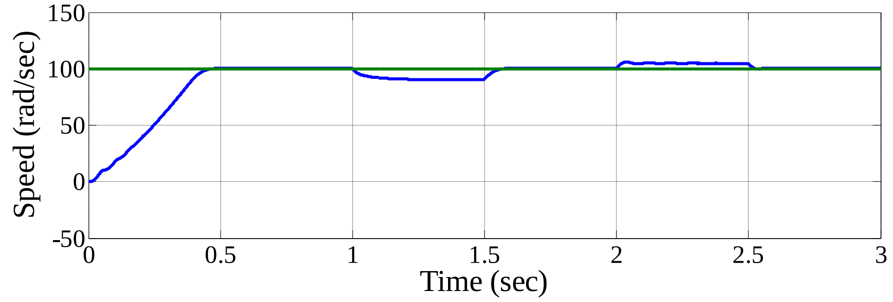


Fig.5.8 Speed-Time Curve

Fig.5.7 shows load torque applied and developed torque of induction motor. Fig.5.8 shows the speed variation due to the load torque variation. From the above results, it is clearly visible that with load torque variation speed is following the reference speed after a speed variation.

C) Results Using CHB eleven-level Inverter

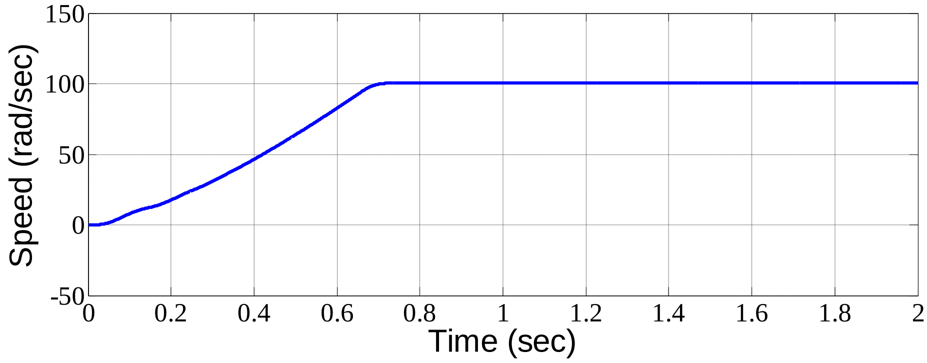


Fig.5.9 Speed-Time Curve

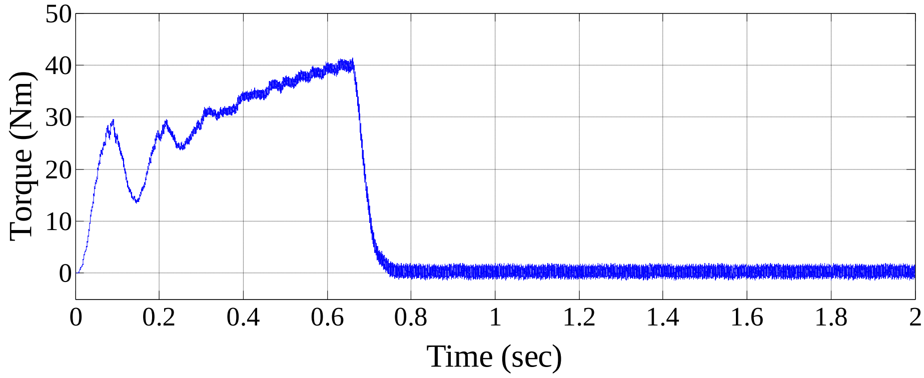


Fig.5.10 Developed Torque

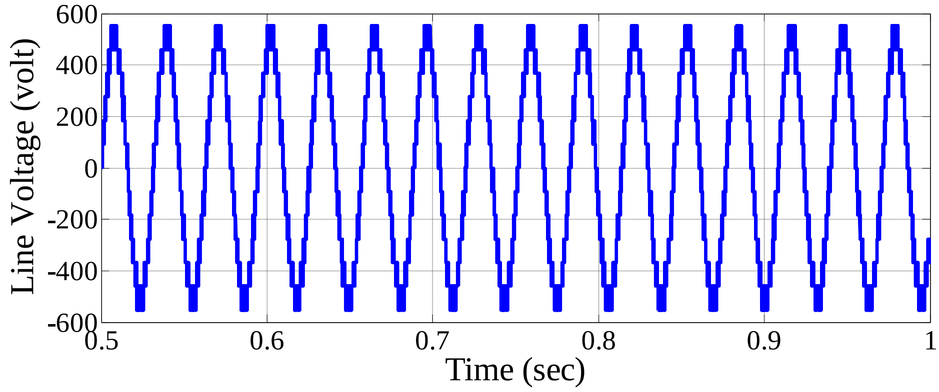


Fig.5.11 Line voltage fed to the motor

Fig.5.9 and Fig.5.10 show the speed time curve and torque developed by the induction motor respectively. Fig.5.11 shows the line voltage fed to the induction motor with 11-level cascaded H-bridge inverter.

The simulation of V/f control of induction motor using MATLAB/SIMULINK was done and simulation results were presented. From the outputs obtained it is clearly observed that the average line-to-line voltage waveform of three-phase 11-levelinverter is almost sinusoidal. Hence, harmonic content in the line voltage fed to the motor will be less. Again, this voltage waveform was achieved with low switching frequency, which resulted in less voltage stress on each switching device.

5.4 Direct Torque and Flux Control (DTFC or DTC)

Electric Vehicle (EV) propulsion system using induction motor drive employing Direct Torque Control (DTC) is becoming popular because of quick response and simple configuration [49]. This method consists of the control of the torque and the stator flux directly, based on their instantaneous errors. It allows a precise and a quick control of flux and torque of the induction motor. This strategy is extensively used in electric vehicle application.

A block diagram of the Direct Torque Control scheme is presented in Fig.5.12. DTC comprises three basic functions: hysteresis control for torque and flux, an optimal switching vector look-up table and a motor model. The motor model estimates the developed torque, stator flux and shaft speed based on the measurements of two stator phase currents and battery voltage (U_{dc}). Actual speed is compared with the reference speed; the error between the actual speed of the motor and reference speed is then given to a speed controller which is a PI controller, and its output gives the reference value of electromagnetic torque (T_{ref}). In DTC speed sensor is not necessary for the torque and flux control. Torque and flux references are compared with their estimated values and control signals are produced by using a torque and flux hysteresis control method. The output of hysteresis controller is then given to the vector look-up table. The switching vector look-up table (Table 5.3) gives the optimum selection of the switching vectors for all the possible stator flux-linkage space-vector positions. The angle of the calculated flux passes to the position of flux, which determines the region where the flux vector is excited, and then the output signal passes through switching table.

The signals of switching table operate the inverter with the optimum state. So, space vector of the inverter voltage depends on the following states:-

i. The angle of flux vector and the direction of the flux vector rotation.
ii. The Value of flux error.
iii. The value of torque error.

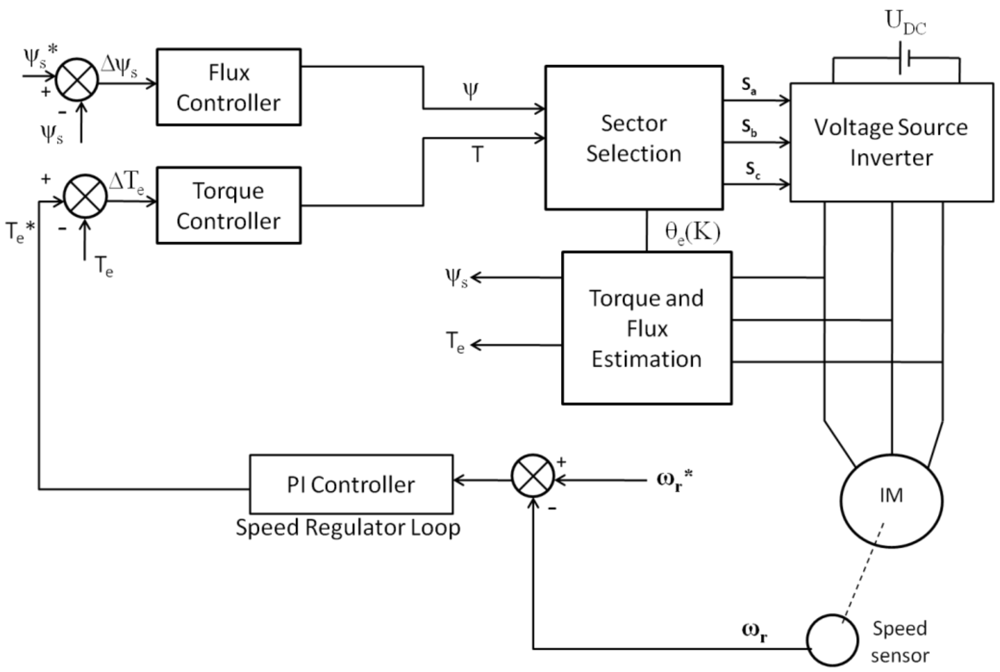


Fig.5.12 Block Diagram of Direct Torque and Flux Control

5.4.1 Mathematical Model of Induction Motor Drive (IMD):

The dynamic model of the induction motor is derived by transforming the three-phase quantities into two-phase direct and quadrature axes quantities. This transformation is done by using park's transformation. Transformation of three-phase rotational frame to two-phase stationary frame is done by following equation:

$$\begin{bmatrix} U_{qs} \\ U_{ds} \\ U_{0s} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} * \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \tag{5.1}$$

The mathematical model in compact form can be given in the stationary reference frame.

$$\begin{bmatrix} U_{ds} \\ U_{qs} \\ U_{dr} \\ U_{qr} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & 0 & L_m p & 0 \\ 0 & R_s + L_s p & 0 & L_m p \\ L_m p & \omega_r L_m & R_r + L_r p & \omega_r L_r \\ -\omega_r L_m & L_m p & -\omega_r L_m & R_r + L_r p \end{bmatrix} * \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \tag{5.2}$$

The flux equation of motor is as follows:

$$\begin{bmatrix} \psi_{ds} \\ \psi_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} * \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \tag{5.3}$$

Where U_{ds}, U_{qs}, U_{dr}, U_{qr}, i_{ds}, i_{qs}, i_{dr}, i_{qr}, L_s, L_r, L_m, R_s, R_r, ψ_{ds}, ψ_{dr}, ψ_{qs}, ψ_{qr} and θ_e are d-q axes voltages, currents, stator inductance, rotor inductance, mutual inductance between stator and rotor windings, stator resistance, rotor resistance, stator and rotor flux linkages and rotor position respectively.

5.4.2 Voltage Source Inverter (VSI):

From the Fig.5.12 S_a, S_b, and S_c are the inputs to the Voltage Source Inverter and S_a, S_b, S_c are the switching functions which can take either logic “1” or logic “0” according to which the switches of inverter get turned on or off. The stator phase voltages are estimated using the equation (5.4) and (5.5):

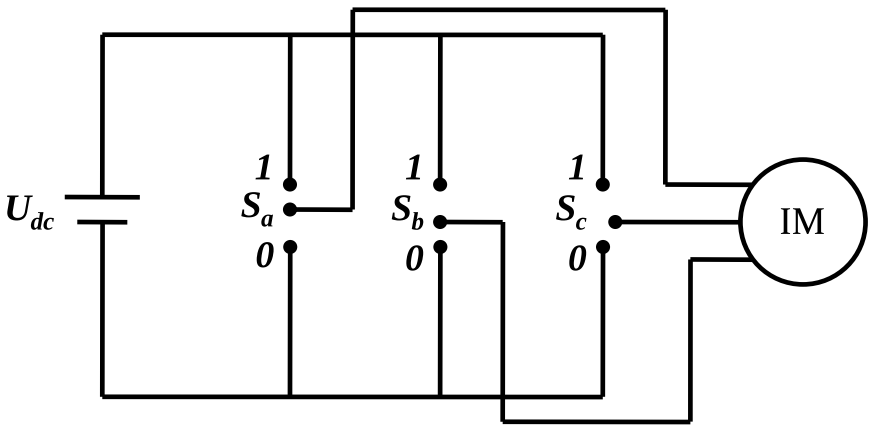


Fig.5.13 Two-level Voltage Source Inverter

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = \frac{U_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \tag{5.4}$$

Where, U_{dc} is the DC link voltage of the inverter. U_a, U_b, U_c can be converted to U_{ds}^s and U_{qs}^s by using following equation:

$$\begin{bmatrix} U_{ds}^s \\ U_{qs}^s \end{bmatrix} = \frac{U_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix} * \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \tag{5.5}$$

5.4.3 Controllers Used in Direct Torque Control (DTC):

In a direct torque control of induction motor drive is supplied by a three-phase voltage source inverter, the main aim is to directly control the stator flux linkage or magnetizing flux linkage or rotor flux linkage and electromagnetic torque by the selection of proper inverter switching states. The switching state selection is made to restrict the flux and torque across within respective flux and torque hysteresis bands and to get low inverter switching loss, fast dynamic response and harmonic distortion in stator currents. Based on the capability of the motor, the voltage vector proportional to the demanded torque and speed can be optimally chosen. The optimal control of the motor will be performed by an optimal switching pattern. For this purpose, acceptable tolerances of the torque and flux errors must be defined. For controlling torque and flux independently two controlling loops are required, Flux hysteresis control loop and torque hysteresis control loop.

A) Flux Hysteresis Control Loop:

This loop consists of a 2-level hysteresis controller to control the flux error. Flux error is generated from the reference flux and actual flux. The stator flux is forced to follow the reference value within ahysteresis band by using a 2-level hysteresis comparator.DTC requires the torque, flux linkage computation and generation of vector switching states through a feedback control of the flux and torque directly. The stator flux in the stationary reference frame (d^s-q^s) can be estimated as:

$$\psi_{ds}^s = \int U_{ds}^s - i_{ds}^s R_s \; dt \tag{5.6}$$

$$\psi_{qs}^{s} = \int U_{qs}^{s} - i_{qs}^{s} R_{s} \; dt \tag{5.7}$$

The estimated stator flux, ψ_s , is given by

$$\psi_{s} = \sqrt{\left({\psi_{ds}^{s}}^{2} + {\psi_{qs}^{s}}^{2} \right)} \tag{5.8}$$

Generally, the stator flux linkage can be obtained from the stator voltage vector as from equation 5.6 and 5.7 Neglecting stator resistance R_s, it may be simplified as:

$$U_{s} = \frac{d}{dt} \psi_{s} \qquad \text{or} \qquad \Delta\psi_{s} = U_{s}\Delta t \tag{5.9}$$

The change in input to the flux hysteresis controller can be written as:

$$\Delta\psi_{s} = \psi_{s}^{*} - \psi_{s} \tag{5.10}$$

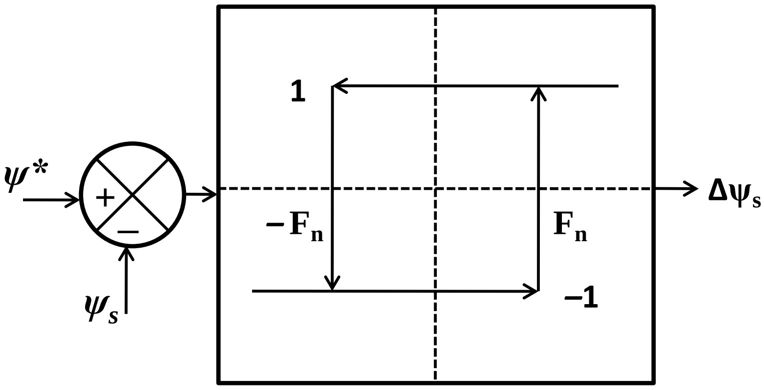


Fig.5.14 Two-level hysteresis controller for controlling the flux error

Fig.5.13 shows the two-level hysteresis controller for controlling the flux error. The flux hysteresis loop controller has two level of digital output according to the relation shown in Table 5.1.

Table 5.1 Switching Logic for Flux error

State	Flux Hysteresis (ψ)
$(\psi_s^* - \psi_s) > \Delta\, \psi_s$	1 ↑
$(\psi_s^* - \psi_s) < -\Delta\, \psi_s$	-1 ↓

B) Torque Hysteresis Control Loop:

The torque hysteresis loop control has three levels of digital output which is shown in Fig.5.14 with relations shown in Table 5.2. When the torque hysteresis band is T_n=1 increasing torque, when T_n=0 means no need to change and T_n= –1 decreasing the torque.

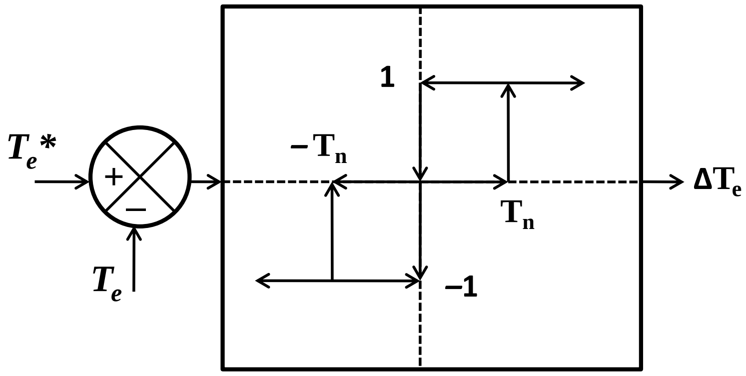


Fig.5.15 Three-level Hysteresis Controller for Control of Torque Error

Table 5.2 Switching Logic for Torque Error

State	Torque Hysteresis (T)
$(T_e^* - T_e) > \Delta T_e$	1 ↑
$-\Delta T_e < (T_e^* - T_e) < \Delta T_e$	0 =
$(T_e^* - T_e) < -\Delta T_e$	-1 ↓

The instantaneous electromagnetic torque and angle in terms of stator flux linkage is given in equation (5.6) and (5.8)

$$T_e = \frac{3}{2}\frac{P}{2}\ \psi_{ds}^s i_{qs}^s - \psi_{qs}^s i_{ds}^s \tag{5.9}$$

Where T_e , P , ψ_{dr} , and ψ_{qr} are the electromagnetic torque, number of poles and rotor d-q axes fluxes respectively. The electromagnetic torque T_e can be expressed as a function of the stator flux and the rotor flux space vectors and the angle between stator and rotor flux linkage space vectors (θ_e) as follows:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{\sigma L_r L_s}|\psi_r||\psi_s|\sin\theta_e \tag{5.11}$$

Where σ (Leakage coefficient) and

$$\sigma = 1 - \ L_m^2 / L_s L_r$$

The angle between stator and rotor flux linkage space vectors (θ_e) is as follows:

$$\theta_e\ k\ = \tan^{-1}\ \psi_{qs}^s / \psi_{ds}^s \tag{5.12}$$

The change in electromagnetic torque error can be written as:

$$\Delta T_e = T_e^* - T_e \tag{5.13}$$

5.4.4 Voltage Vector Switching Selection

The voltage vector switching selection using torque or flux need to be increased or decreased comes from the three level and two level hysteresis comparators of torque and stator flux respectively. Fig.5.13 shows the sectors and voltage. Table 5.3 shows the voltage vector switching selection for Voltage source inverter. Table 5.4 shows the relation between torque and flux due to the application of voltage vectors. Voltage vectors V_2, V_3, V_4 are applied when torque is to be increased and V_1, V_5, $V_{6,}$ $V_0/V_7$are applied when torque is to be decreased. Voltage vectors V_1, V_2, V_6 are applied when flux is to be increased and V_3, V_4, V_5 are applied when flux is to be decreased. Application voltage vectors V_0 and V_7 do not affect the flux. V1, V2, V3, V4, V5, V6 are the active voltage vectors and V0 and V7 are zero vectors.

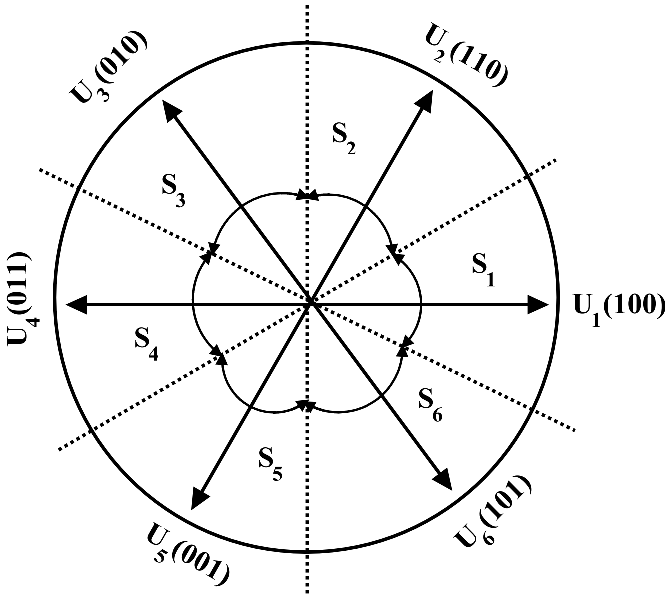


Fig.5.16 Sectors and voltage vectors

Table 5.3 Switching Table of Inverter Voltage Vectors

Hysteresis Controller		Sector Selection θ_e(K)					
ψ	T	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)
1	1 ↑	U_2	U_3	U_4	U_5	U_6	U_1
	0 =	U_0	U_7	U_0	U_7	U_0	U_7
	–1 ↓	U_6	U_1	U_2	U_3	U_4	U_5
–1	1 ↑	U_3	U_4	U_5	U_6	U_1	U_2
	0 =	U_0	U_7	U_0	U_7	U_0	U_7
	–1 ↓	U_5	U_6	U_1	U_2	U_3	U_4

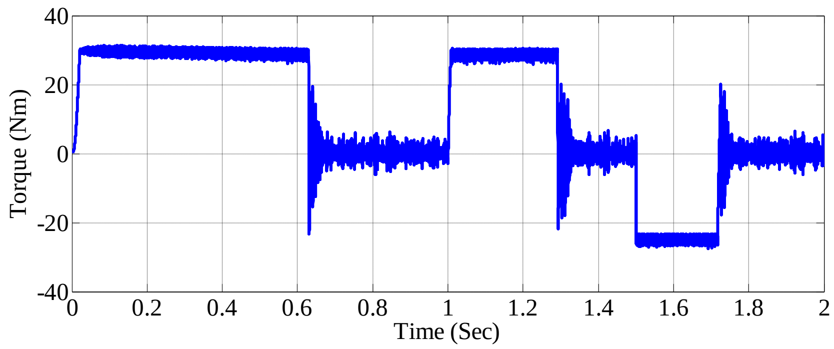
Table 5.4 Flux and Torque Variation Due to application of Voltage Vectors

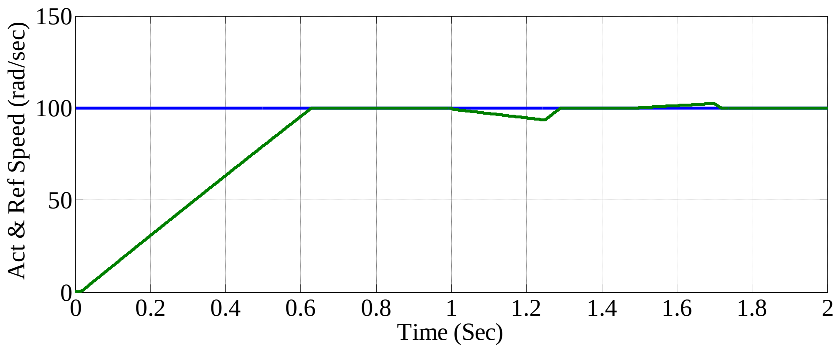
Voltage Vector	V_1	V_2	V_3	V_4	V_5	V_6	V_0 or V_7
ψ_s	↑	↑	↓	↓	↓	↑	0
T_e	↓	↑	↑	↑	↓	↓	↓

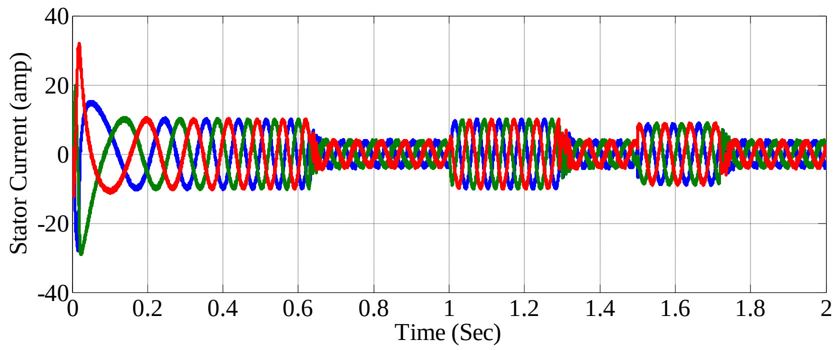
5.5 Simulation Results

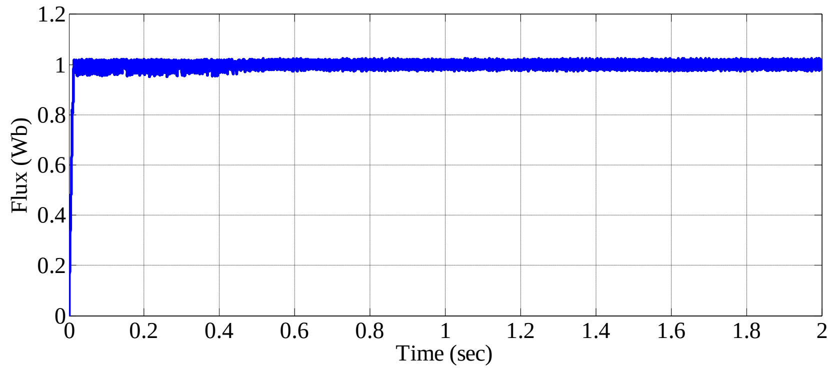
By using MATLAB/SIMULINK environment, a simulation model of DTC of induction motor has been implemented. A 3-phase, 5 HP, 400V induction motor was taken to control its flux and torque. Machine specifications are given in Appendix-I. A starting torque of 30 N-m, a reference flux of 1.0 Wb and a reference speed of 100 rad/sec were set. A PI controller was used to track the reference speed.

A) Results with Load Variation









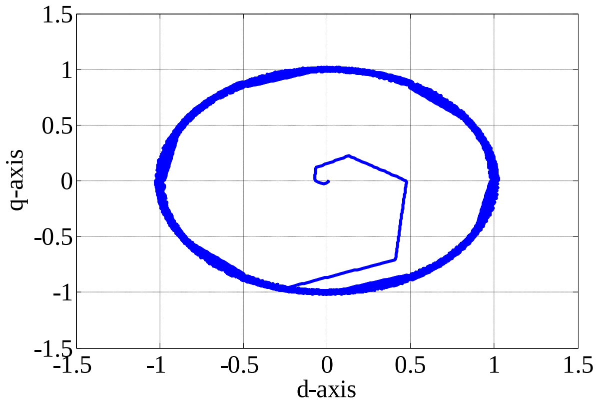
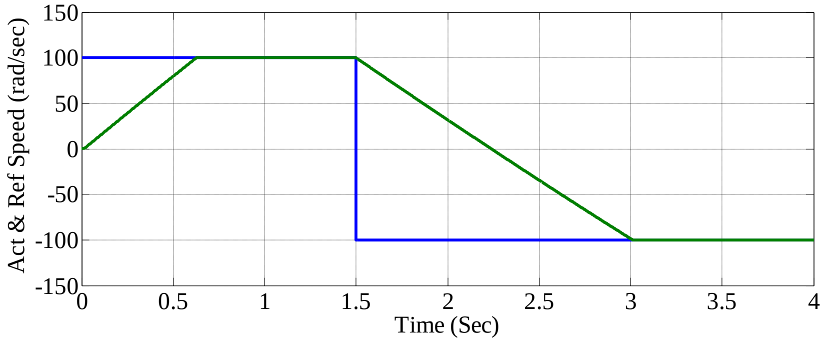


Fig.5.17 Developed Torque, Reference and Actual speed, Stator Current, Flux Vs time curve, Flux response (d-q axis)

Fig.5.16 shows the transient response of developed torque, reference and actual speed, stator current, flux Vs time and flux response (d-q axis) of induction motor in transient condition when a load torque of 30 N-m was applied at 1sec and removed at 1.3 sec and a negative load torque of -20 N-m was applied at 1.5 sec and removed at 1.7 sec. In this case, results were taken with constant speed command. From the figure it is clearly observed that a high inrush current is drawn by the motor during starting i.e. from 0 to 100 rad/sec. By first establishing the flux with zero speed or torque command for the first few cycles and by giving the constant speed command to the drive, this high inrush current can be minimized. Also, the figure shows that the three-phase stator currents are close to sinusoidal.

B) Results with Speed Reversal



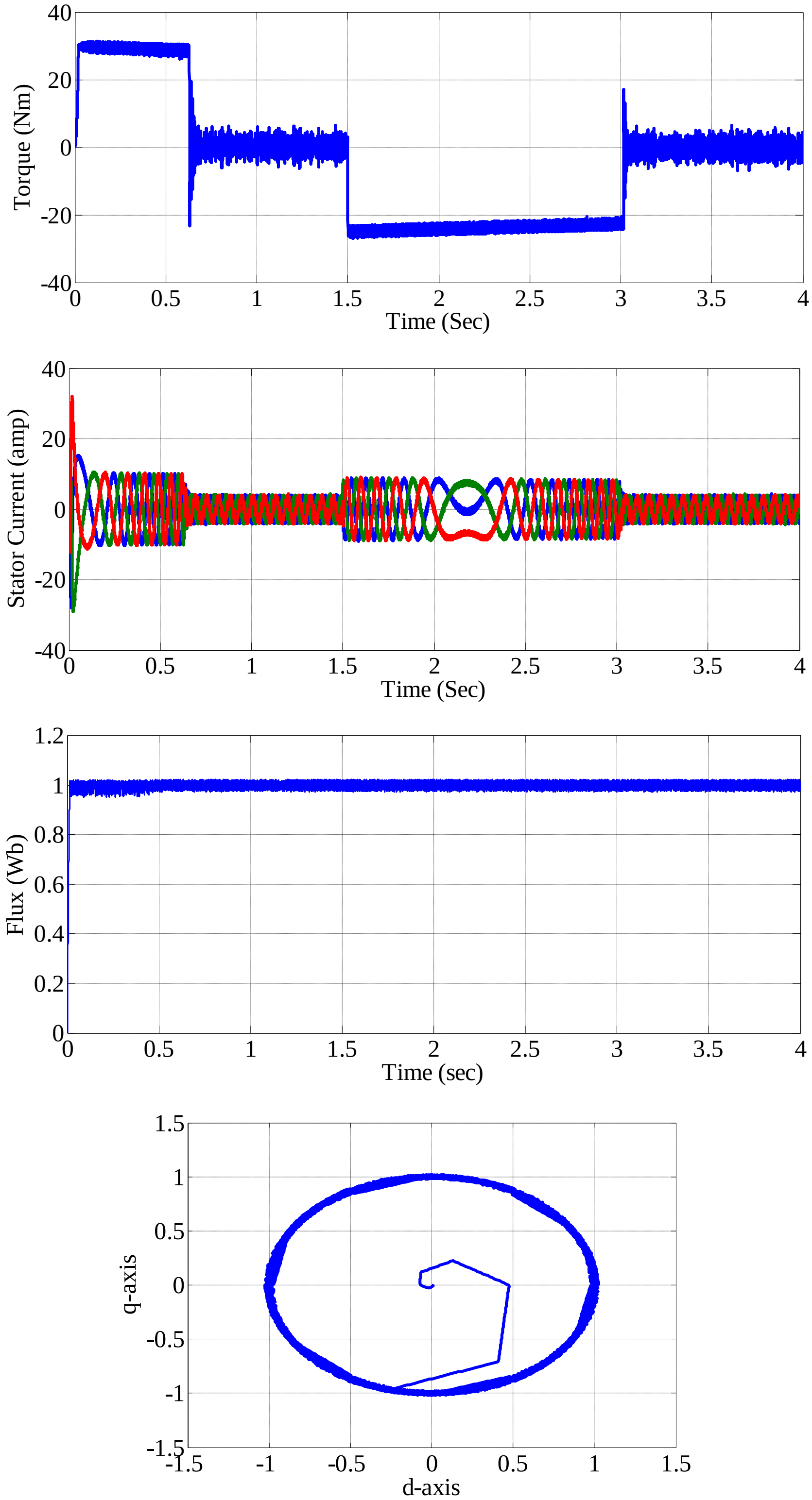


Fig.5.18 Developed Torque, Reference and Actual speed, Stator Current, Flux Vs time curve, Flux response (d-q axis)

Fig.5.17 shows the transient response of developed torque, reference and actual speed, stator current, flux Vs time, and flux response (d-q axis) of induction motor during speed reversal from 100 rad/sec to -100 rad/sec. From the above figure it is clearly visible that the phase sequences of motor currents get reversed during the speed reversal from 100 rad/sec to -100 rad/sec at 1.5 sec.

5.6 Summary

By using MATLAB/SIMULINK environment, simulation models of speed control of induction motor by V/f control and DTC have been implemented. In DTC, two independent torque and flux hysteresis band controllers were used in order to control the limits of the torque and flux. Simulation results were taken by varying the load torque and by varying the reference speed. DTC method was found to give better results than V/f control.

CHAPTER 6

6. CONCLUSION AND SCOPE FOR FUTURE WORK

6.1 Conclusion

The three level, five level, seven level, nine level and eleven level cascaded H-bridge inverters were simulated in MATLAB/SIMULINK environment. Two types of Multicarrier Pulse Width Modulation-Level Shifted Modulation and Phase Shifted Modulation and SHE modulation technique were implemented for the cascaded multilevel inverter. The following things can be concluded about the modulation techniques and the multilevel inverters:

1. Level Shifted Modulation was found to have better THD values as compared to Phase Shifted Modulation.
2. Among the Level Shifted Modulation techniques, the In Phase Disposition (IPD) modulation technique was better in terms of THD.
3. As the number of levels in the output voltage of the inverter increases, the synthesized waveform has more steps, which produces a staircase waveform that approximates to a sinusoidal waveform which is required.
4. Also as the level of the output voltage increases, the harmonic distortion of the output Voltage waveform decreases.
5. Selective Harmonic Elimination (SHE) Modulation Technique was found to be better in comparison to the above mentioned modulation techniques. The THD of the output line voltage of the eleven- level inverter is comparatively low (less than 5%).

Thus, on comparison it was found that SHE technique is best suitable for the cascaded eleven-level inverter. Hence, this technique was implemented in cascaded rectifier also. The cascaded rectifier inverter configuration with SHE modulation was used in the railway traction drive. It was found that the cascaded rectifier inverter configuration gave sinusoidal output waveform. This converter system can meet the power or voltage requirement of the traction drive. The cascaded eleven level converter system modelled in this project can be used in traction drive consisting of six induction motors for stepping down the catenary voltage to the rated voltage of the induction motors. Thus, this model eliminates the necessity of the transformer in railway traction and hence lowers the cost and floor space and increases the efficiency of the traction drive.

In order to control the speed of traction motor, two speed control strategies like closed-loop speed control with V/f control and slip regulation and DTC were employed. V/f control scheme controls the speed of the motor by keeping the flux of the motor constant. Here flux and torque are not controlled directly. In DTC, speed of the induction motor is controlled by directly controlling the torque and flux of the induction motor. Hence, DTC scheme was found to give better result than V/f control scheme.

6.2 Scope for Future Work

i. Direct Torque Control (DTC) strategy can be employed with Space Vector Modulation to reduce the torque ripples.
ii. DTC can be employed using multilevel inverter to have better results.

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APPENDIX-I

The specification and the parameters of the induction motor:

Power = 5HP, line-line Voltage=400V, Frequency = 50Hz, Stator Resistance R_s = 1.405, Stator Inductance L_s =0.005839 H, Rotor Resistance R_r = 1.395 Ω, Rotor Inductance L_r = 0.005839 H, Mutual Inductance L_m = 0.1722H, Moment of Inertia J=0.2 kg-m2, Frication Factor B=0.002985 kg-m^2/s.